U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB-269 382

Comprehensive Summary of Sludge Disposal Recycling History

Metropolitan Denver Sewage Disposal Dist. No 1, Commerce City, CO

Prepared for

Municipal Environmental Research Lab, Cincinnati, Ohio Wastewater Research Div

Apr 77

PB 269 352

REPRODUCED BY
NATIONAL TECHNICAL
INFORMATION SERVICE

TECHNICAL REPORT DATA (Please read Instructions on the reverse before completing)	
1. REPORT NO. EPA-600/2-77-054	2. RECIPIENT'S ACCESSION NO.
4. TITLE AND SUBTITLE COMPREHENSIVE SUMMARY OF SLUDGE DISPOSAL RECYCLING HISTORY	5. REPORT DATE April 1977 (Issuing Date) 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) John C. Baxter, William J. Martin, Burns R. Sabey, William E. Hart, David B. Cohen, and Carl F. Calkins	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Metropolitan Denver Sewage Disposal District No. 1 3100 East 60th Avenue Commerce City, Colorado 80022	10. PROGRAM ELEMENT NO. 1BC611 11. CONTRACT/GRANT NO. 68-03-2064
12. SPONSORING AGENCY NAME AND ADDRESS Municipal Environmental Research Laboratory--Cin.,OH Office of Research and Development U.S. Environmental Protection Agency Cincinnati, Ohio 45268	13. TYPE OF REPORT AND PERIOD COVERED Final 1967-1976 14. SPONSORING AGENCY CODE EPA/600/14
15. SUPPLEMENTARY NOTES	

16. ABSTRACT

Since 1971 the only mode of sludge disposal used by Metro has been land application. A number of different application procedures have been tried over the intervening years. The development of methodology and problems associated with each procedure are discussed in the text.

Continuous applications of sludge to the soil at the Lowry Bombing Range since 1969 have raised the concentration of nutrients, metals, salts and organic matter. The effects of these excessive loading rates on the soil, crops and environment are evaluated.

The effects of various sludge applications to soil on germination, emergence, subsequent plant growth, and uptake of heavy metals are examined. Inhibition of germination decreased with increasing soil sludge incubation periods or when dried sludge was used, suggesting that salts or some volatile component within the sludge was inhibiting germination.

Microbial counts of fecal coliform bacteria in sludged plots showed no appreciable differences from control plots after a 6 month incubation period.

Liquid sludge added to shallow earthen drying basins demonstrated that water is lost through soil percolation in addition to evaporation, and that about half the N content of sludge is lost. A discussion of future research needs is also included in the text.

17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Sludge disposal Soil properties Land reclamation Land use Fertilizer Organic wastes	Municipal wastes Crop response Heavy metals Sludge recycling Land application Recycling history	13B
18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS (This Report) UNCLASSIFIED 20. SECURITY CLASS (This page) UNCLASSIFIED	21. NO. OF PAGES 22 22. PRICE PC A02 / MF A01

EPA Form 2220-1 (9-73)

EPA-600/2-77-064
April 1977

COMPREHENSIVE SUMMARY OF SLUDGE DISPOSAL RECYCLING HISTORY

by

John C. Baxter*
William J. Martin*
Burns R. Sabey**
William E. Hart**
David B. Cohen*
Carl F. Calkins*

*Metropolitan Denver Sewage Disposal District No. 1
Commerce City, Colorado 80022

**Colorado State University
Fort Collins, Colorado 80521

Contract No. 68-03-2064

Project Officer

James A. Ryan
Wastewater Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

DISCLAIMER

This report has been reviewed by the Municipal Environmental Research Laboratory, U. S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U. S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This history of land utilization of wastewater sludge was conducted for the Ultimate Disposal Section of the Wastewater Research Division to gain insight into the ramifications of land application when used by a large municipality, as well as to document the results of the Metropolitan Denver Sewage Disposal District No. 1 in their efforts to utilize this process.

Francis T. Mayo
Director
Municipal Environmental Research
Laboratory

Piles of Ordure

Do you know what these piles of ordure are,
Collected at the corners of streets,
Those carts of mud carried off at night from streets,
The frightful barrels of the nightmen,
And the fetid streams of subterranean mud
Which the pavement conceals from you?

All this is a flowering field,
  it is green grass, it is mint, thyme and sage;
It is game, it is cattle,
  it is the satisfied lowing of heavy kine;
At night it is perfumed hay,
  it is gilded wheat,
  it is bread on your table,
  it is warm blood in your veins,
  it is health, it is joy, it is life!

Victor Hugo, in Les Miserables (1862)

ABSTRACT

Processing and ultimate disposal of wastewater sludge is one of the most costly unit processes within any sewage treatment plant. Since 1969 the Metropolitan Denver Sewage Disposal District No. 1 (Metro) has been examining methods of sludge disposal which are both economical and environmentally sound. The original flash-dryer incinerator units installed at Metro proved to be costly and environmentally unacceptable, therefore, land application became a viable alternative to flash drying or incineration.

Since 1971 the only mode of sludge disposal used by Metro has been land application. A number of different application procudures have been tried over the intervening years. The development of methodology and problems associated with each procedure are discussed in the text.

Continuous applications of sludge to the soil at the Lowry Bombing Range since 1969 have raised the concentration of nutrients, metals, salts and organic matter. The effects of these loading rates on the soil, crops and environment are evaluated.

The effects of various sludge applications to soil on germination, emergence, subseqeunt plant growth and heavy metals uptake are discussed. Improved wheat yields were experienced with sludge application rates up to 50 metric tons per hectare. Low germination and emergence rates were found when crops were planted immediately after sludge incorporation. Inhibition of germination decreased with increasing soil sludge incubation periods or when dried sludge was used, suggesting that salts or some volatile component within the sludge was inhibiting germination. Sorghum sudangrass was most inhibited by sludge additions, and was affected to some extent by all sludge treatments. Corn was intermediate in tolerance, and wheat was the least affected by sludge additions. There appeared to be no inhibition of germination and emergence of wheat and corn after an incubation period of one month.

Microbial counts showed that sludged plots had an appreciable increase in total aerobic, total colliform and fecal streptococci bacteria. Counts of fecal colliform bacteria demonstrated that there were no appreciable differences between the sludged and control plots.

Experiments examining the possibility of air drying anaerobically digested liquid sludge in shallow earthen drying basins demonstrated that water is lost through soil percolation in addition to evaporation, and that about half of the nitrogen (N) content of sludge is lost during the drying process. A discussion of future research needs is also included in the text.

CONTENTS

Foreword iii
Abstract v
Figures viii
Tables ix

I. Introduction 1
II. Initial Experiences in Sludge Handling and Disposal 3
III. Development of Land Application Technology 6
IV. Evaluation of Sludge Disposal at the Lowry Bombing Range 14
A) Type of Sludge 14
B) Soil Effects of Sludge Disposal at the Lowry Bombing Range ... 16
V. Research and Development 23
A) Land Application of Metro Sewage Sludge at Watkins, Colorado. 24
1) Materials and Methods 24
2) Results and Discussion 28
3) Conclusions 42
B) The Effect of Metro Sludge on Germination and Plant Growth of Three Crops in a Greenhouse Study 43
1) Materials and Methods 43
2) Results and Discussion 44
3) Conclusions 48
C) Sludge Air Drying Project 51
1) Materials and Methods 51
2) Results and Discussion 51
3) Conclusions 56
VI. Future Agricultural Research and Development Projects 57
VII. Appendix 70
VIII. Glossary 84

Preceding page blank

FIGURES

NO.		PAGE
1.	Filter cake sludge being tailgated onto soil surface.	5
2.	Location map of Lowry Bombing Range sludge recycle site.	6
3.	Sludge being transferred to 10 cubic meter manure spreaders.	9
4.	Transport vehicle dumping into sludge storage hopper.	10
5.	Modified fertilizer spreader broadcasting sludge.	11
6.	Mold board plow incorporating sludge.	12
7.	Lowry Bombing Range sludge recycle site showing areas used for soil monitoring; shaded areas represent fields to which sludge has been applied.	16
8.	Plot design layout with identification and loadings (dry metric tons per hectare) of each plot.	26
9.	1978 wheat yield on filter cake plots.	32
10.	pH of soil profile with various rates of sewage sludge additions.	34
11.	Electrical conductivity of soil with various rates of sewage sludge application.	34
12.	Organic matter content of soil with various rates of sewage sludge additions.	35
13.	NO_3-N of soil with various rates of sewage sludge additions.	36
14.	Available P content of soil with various rates of sewage sludge additions.	36
15.	Available K content of soil with various rates of sewage sludge additions.	37
16.	DTPA extractable Zn content of soil with various rates of sewage sludge additions.	37
17.	DTPA extractable Fe content of soil with various rates of sewage sludge additions.	38
18.	DTPA extractable Cu content of soil with various rates of sewage sludge additions.	38
19.	DTPA extractable Mn content of soil with various rates of sewage sludge additions.	39

TABLES

NO.		PAGE
1	Comparison of incinerator versus land application sludge disposal costs	10
2	A comparison of chemical composition of ferric chloride and lime treated vacuum filter cake with polymer conditioned vacuum filter cake (1972-1975 data)	15
3	Concentrations of DTPA extractable Zn, Fe, Cu, Mn and pH from sludge additions to surface soils (0-15.24 cm) at the Lowry Bombing Range	17
4	Comparison of chemical constituents of soil samples taken at Lowry in May 1974 and November 1974	19
5	Concentrations of NO_3-N, NH_4-N, TKN, P, K and conductivity from sludge additions to surface soils (0-15.24 cm) at the Lowry Bombing Range	20
6	Concentrations of NO_3-N, NH_4^+-N and TKN from subsurface soils (61 to 91 cm depth) at the Lowry Bombing Range	21
7	Total metal composition of soil and wheat from the Lowry Bombing Range	22
8	Characteristics of the Truckton loamy sand used in the study	24
9	Typical analysis of anaerobically and aerobically digested sewage sludge produced by the Metropolitan Denver Sewage Disposal District No. 1	25
10	Germination and emergence counts on July 20, 1971 for three rows, each 7.65 meters long	29
11	Wheat stand counts on October 19, 1971 for three rows, each 1.83 meters long	29
12	Yield and nitrogen content of sorghum sudangrass as affected by sludge application rate	30
13	Effect of sewage sludge addition to Truckton loamy sand on winter wheat yields, 1972	31
14	Total elemental composition of wheat grain as influenced by rate of Metro sewage sludge addition	32
15	8.1 hectare filter cake demonstration showing wheat yields in kilograms dry matter per hectare	33
16	Bacterial counts of soil samples taken from fields (fallow and sorghum sudangrass) treated with sewage sludge	40
17	Average values for infiltration rates on sludge treated soils	40
18	Significant variables found in modeling water applications of 1.27, 2.54, 5.08 and 10.16 centimeters	42
19	Rate of sludge applications to Truckton sandy loam soil	43
20	Soil incubation periods and corresponding planting, thinning and harvest data	44

NO.		PAGE
#1a	The effect of sewage sludge on germination and emergence of seeds of three crops. Seeds planted one month after the treatments were mixed with soil	45
#1b	Seeds planted three months after the treatments were mixed with soil	46
#1c	Seeds planted six months after the treatments were mixed with soil	47
#2	The effect of sewage sludge on early growth (two weeks after planting) of three crops grown in a greenhouse	49
#3	The effect of sewage sludge on oven dry weight of three crops grown in a greenhouse for 2 to 3 months	50
#4	Initial depth of liquid sludge	52
#5	Change in percent total solids content of drying basin with time	52
#6	Net evaporation required (centimeters per year) at various sludge loading rates	54
#7a	Nitrogen concentration of 3 layers of liquid sludge in drying basins	55
#7a	Nitrogen concentration as a percent of the total solids concentration of the three stratified samples	55
#8	Range in various chemical constituents of liquid sludge contained in drying basins	56

INTRODUCTION

Sludge handling and disposal are the most problematic and costly unit processes in wastewater treatment, particularly for large municipal wastewater treatment facilities. At the Metropolitan Denver Sewage Disposal District No. 1 (Metro) the cost of sludge disposal has been continuously increasing. During 1974, sludge handling and disposal accounted for over one-half of the total annual operation and maintenance budget.

Ultimate disposal of residues removed by the treatment process must enter the ecosystem via one or more of three alternate pathways, land, atmosphere or water. Since the Metro plant went on-line in 1966, three alternate sludge disposal pathways have been utilized, each with particular advantages and disadvantages. The water pathway for sludge disposal is particularly inappropriate in a semi-arid climate such as eastern Colorado where water resources are seriously limited and must be protected. Inadvertent air pollution by incineration or other means is rapidly becoming socially unacceptable. This is particularly so in Denver where altitude and topography combine to make air pollution entrapment during temperature inversions a serious concern. Having ruled out the air and water pathways by trial and error, the only remaining alternative for Metro was the application of sewage sludge residues to land.

One possible method of land application involves sanitary landfilling or burial of ash obtained from incineration of sewage sludge. While incineration provides a relatively inert residue which can be disposed of on land, this method has certain drawbacks. In addition to air pollution, incineration destroys a potential resource. The increasing awareness of the finite limitations of natural resource development has led to a search for new uses for what have previously been considered wastes. Sewage sludge is a major untapped resource which contains significant concentrations of nitrogen, phosphorous, micronutrients, and humic materials. While this fact has been known for years, the relatively low cost of synthetic commercial fertilizer and soil amendment materials inhibited the farming community from exploiting sewage sludge for growing crops. Recent economic developments, particularly the diminishing availability of energy and its fertilizer by-products have created a new climate of greater acceptance for the beneficial recycling of sewage sludge to land. However, this alternative also poses potential problems such as heavy metals buildup in soils and plants, pathogen dissemination, and nitrate pollution of ground water. These problems can be overcome by judicious loading rates, cropping, and environmental monitoring.

The Metro District is not unique in having to cope with these problems. The authors of this report hope that other agencies charged with handling of sewage residues can benefit from Metro's experience in pursuit of a solution for economically and ecologically recycling sewage sludge.

The first four sections of this report summarize Metro's sludge handling and disposal history from 1966 to the present time. The fifth and sixth sections describe the research and development efforts to solve existing problems as well as to anticipate future problems. The seventh and final part attempts to summarize the operational and research experience with recommendations for future efforts.

INITIAL EXPERIENCES IN SLUDGE HANDLING AND DISPOSAL

The Metro plant was designed to treat 117 MGD (million gallons per day) of wastewater. The residuals removed in the process were to be dewatered through dissolved air flotation and vacuum filtration, and ultimately disposed of by flash drying and/or incineration. The anticipated ratios of raw primary, anaerobically digested primary and undigested waste activated sludge which comprised the vacuum filter feed sludge were expected to yield a filter cake moisture content of no greater than 70%. The chemicals required for sludge conditioning prior to vacuum filtration were expected to average 65 FeCl3 (ferric chloride) and 10% lime. If these design conditions had been realized, the amount of water requiring evaporation at full plant capacity would have equated 311.2 metric tons per day. The design engineers provided three FDI (flash-dryer incinerator) units each having a maximum evaporative capacity of 5.9 metric tons water per hour. All three units operating at 100% of the designed capacity would have provided a total evaporative capacity of 425 metric tons of water per day.

Early in 1967 it became apparent that the ratio of waste activated sludge to the total sludge mixture was much greater than originally anticipated by the design engineer. The higher quantity of more difficult to dewater waste activated sludge had an adverse effect on the vacuum filter cake solids concentration, which averaged 14% to 18% TS (total solids) instead of the expected 22% to 25%. This adverse sludge ratio increased the original design estimate for chemicals required for vacuum filtration by more than 100%. This sequence of events led to a serious overload condition of the evaporative capacity of the FDI units. Mechanical problems and breakdowns as a result of the overload condition were exacerbated by FeCl3 (ferric chloride) induced corrosion failures of the stainless steel components of the FDI units.

By the fall of 1968 the sludge handling and disposal problem had reached crisis proportions. As a result of mechanical problems, less than half of the evaporative capacity of the FDI units was available for sludge disposal. Activated sludge accumulation in the biological treatment system caused a rapid deterioration of final effluent quality. In order to avoid scouring of activated sludge from the secondary clarifiers into the South Platte River, lagoons were constructed for the temporary storage of excess activated sludge. Sixteen hectares of lagoons representing sixty million gallons of storage capacity provided temporary relief during the winter months of 1968 - 1969. By the spring of 1969, anaerobic decomposition of the waste activated sludge stored in the lagoons created serious odor problems. Neither the FDI units nor the temporary lagoons provided an acceptable solution to the sludge disposal problem. Consequently, a third alternative, land application of vacuum filter cake, was initiated in May of 1969.

land application of vacuum filter cake was originally conceived to be a temporary expedient until the FDI units could be restored to their design capability. By 1971 it was apparent that the cost of continued operation and maintenance of the FDI units would be prohibitive. The most serious problems occurred when the FDI units were being operated in the incineration mode. Although from a maintenance standpoint it would have been desirable to operate the units in the drying mode only, this was not possible for several reasons. The primary fuel source for the operation of the units was natural gas with No. 2 diesel as a standby fuel. During the winter of 1972-1973, natural gas service was curtailed on many occasions, and Metro did not have a sufficient allocation of standby fuel. This limited fuel supply forced the District to incinerate sludge for its calorific value as a substitute for commercial fuel.

It was originally anticipated that the City and County of Denver Parks Department would use the dry sludge as a fertilizer. The physical characteristics of the heat dried sludge were such that it could not be handled with commercial fertilizer spreaders without causing dust problems. For this reason the Denver Parks Department in the fall of 1969 refused to accept any additional dried sludge. As no other large customer of dried sludge existed in the area, it was necessary to cease drying and revert back to the incineration mode even during periods when adequate fuel was available for drying.

Operational limitations encountered during the incineration mode were odors, as well as particulate and opacity air pollution problems. When the FDI units were initially installed in 1966 they met all existing Colorado air pollution standards. In 1970 these standards were revised drastically to reduce stack emission concentrations from stationary sources. During 1971 the FDI units were operated under a temporary variance while modifications were being made to meet the new standards. It soon became obvious that the FDI units could not be economically modified to comply with the new standards. Because of air pollution, mechanical and fuel problems, the FDI units were permanently shut down in August of 1971. Between May of 1969 and August of 1971 the FDI units and the land application of filter cake were operated concurrently. From August of 1971 to the present time the only method of sludge disposal used by Metro has been land application.

EVALUATION OF LAND APPLICATION TECHNOLOGY

In 1969 Metro acquired 64.8 hectares of land from the City and County of Denver. This land had been sold to the City and County of Denver by the federal government for the purpose of solids waste disposal. The land is located 40 kilometers southeast of the Metro treatment plant and was part of the LBR (Lowry Bombing Range) (Fig. 2). The vegetation on this site was natural pasture grass typical of the range land of Colorado. During 1969 and 1970 the vacuum filter cake sludge, which could not be processed by the FDI units, was transported by truck to the LBR site. The vacuum filtered sludge contained 16% TS and was transported in open 10 cubic meter trucks equipped with special rubber seals to prevent leakage during transport.

In 1969 and 1970 two methods of operation were utilized, one for dry weather and the second for wet weather. Metro hired a contractor to perform the necessary work under both modes of operation. The transportation of vacuum filter cake was the same for both dry and wet weather operations. During dry weather the sludge was tailgated directly from the transport vehicle onto the

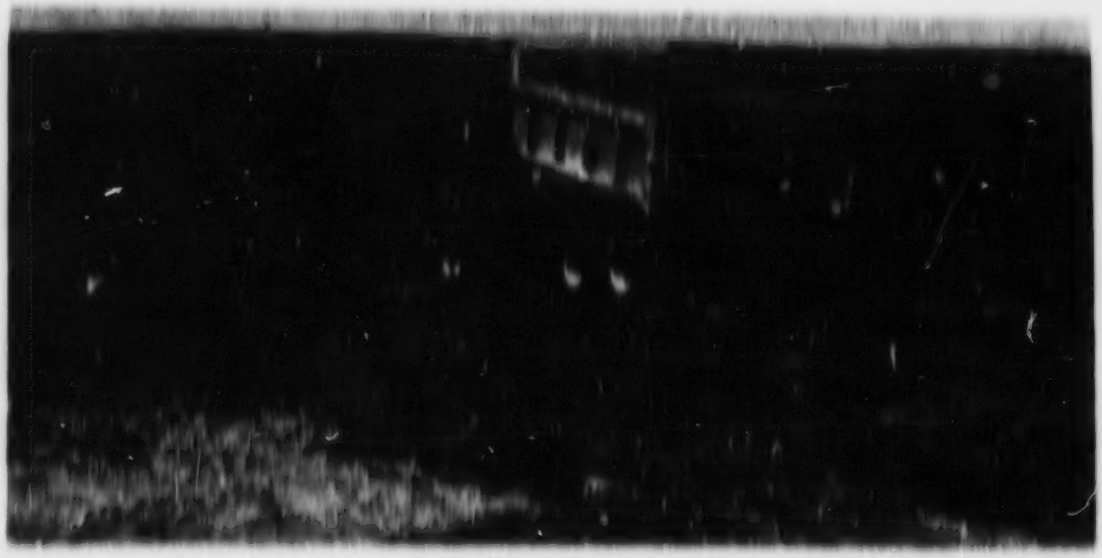

Fig. 1-Filter cake sludge is tailgated onto soil surface.

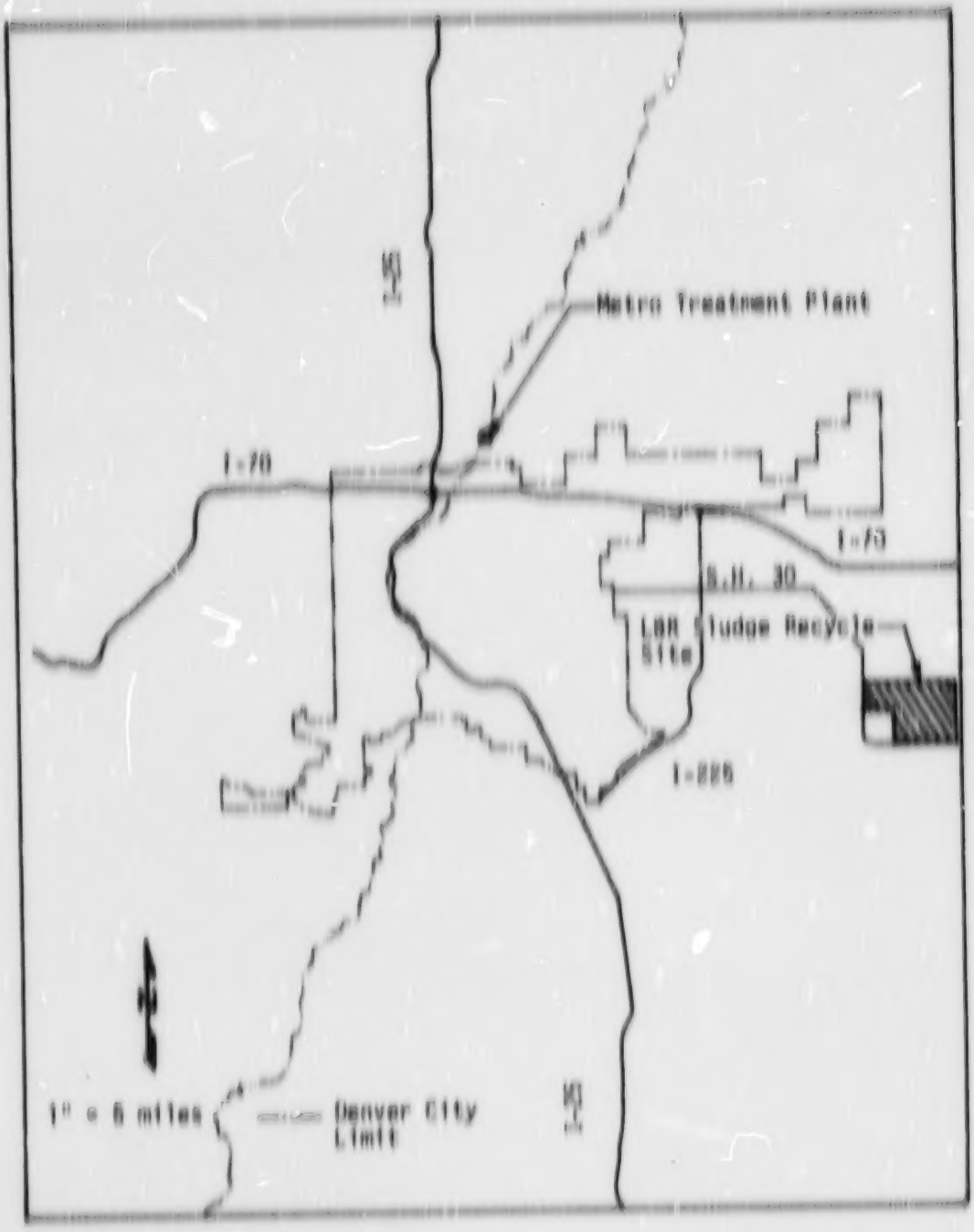

Fig. 2-Location map of Lowry Bombing Range sludge recycle site.

surface of the soil. A D-6 Caterpillar equipped with a front mount blade was then used to spread the sludge evenly over the surface of the soil to a depth of approximately 2.5 centimeters. The sludge was then allowed to dry for 24 hours. After the sludge had dried, an industrial-type (1.8 meter wide) rototiller with a depth capability of 45.7 centimeters incorporated the sludge into the soil. This operation was not always satisfactory for the following reasons:

A) Rocks over 12.7 centimeters in diameter would lodge in the tiller mechanism, causing shear pins and drive chains to fail, thus, rendering the unit inoperable.

B) Dense vegetation over 1.2 meters tall would wrap up in the tiller mechanism and plug the unit.

C) Wet soil would clog the tiller mechanism with mud and the unit would become inoperable.

During warm weather, land application was cyclical, three weeks on and three weeks off, which coincided with shutdown and routine maintenance of the FDI units. In wet weather the sludge was dumped directly onto the surface of the soil, and D-8 Caterpillar tractors with front mounted blades would intermix the sludge with the soil. A satisfactory mix was accomplished when a ratio of five or more parts of soil were mixed with one part of sludge. However, during the winter months when the soil had frozen, the mixing of sludge and soil was extremely difficult. It then became necessary to provide a ripper behind the D-8 Caterpillar in order to keep ahead of the soil freezing problem. It was necessary to work 24 hours a day, 7 days a week. During winter weather operation, the sludge was intermixed into the soil in the rolling topography which lends itself to this type of operation. In these areas large quantities of soil for intermixing with sludge were available within a relatively short distance from the application site. Of the 64.8 hectares originally acquired 36.4 hectares were actually utilized for sludge incorporation. A total of 30,600 dry metric tons were applied to the site in 1969 and 1970 for a loading rate of approximately 840 dry metric tons per hectare. The exact sludge loadings to the area in 1969-1970 could not be determined because of different application methods used at different seasons.

Peripheral surface water channels were dug around the 64.8 hectare site to retain the water which ran off during snow or rain storms. During severe storms the collection channels proved inadequate to contain all of the runoff. Metro and the State Health Department sampled this runoff downstream of the site during these periods. Analysis of the runoff samples did not indicate the presence of contaminants from the land application site.

In April of 1970 Metro ceased application of sludge to the site because of concern that the high loading rates might have an adverse effect on soil productivity and erosion. The site was then graded using a rubber tired scraper (between the fall of 1970 and the spring of 1971). In the fall of 1971 the site was seeded using Brome and Crested Wheat grasses. During 1972 high winds and generally dry conditions hindered growth of the grasses planted. In the spring of 1972 the area was reseeded. Because vegetative coverage

was incomplete, the area was again reseeded in the fall of 1972 with the same mixture of grasses. By the spring of 1973 vegetative coverage exceeded 50% of the total area. Supplementary seedings were conducted during the fall of 1973 and spring of 1974. By the spring of 1975 vegetative cover was virtually complete. The complete revegetation process took three years. Revegetation was difficult because top soil had been removed and replaced with subsoil (no sludge was incorporated into the soil) and moisture was marginal. Annual precipitation averages 38.6 centimeters per year and irrigation water was not available.

The major problem involved in the 1969-1970 operation was vulnerability to adverse climatic conditions. There were several occasions during the winter of 1969 and 1970 when snow blizzards required cessation of sludge incorporation. The equipment operators and truck drivers could not reach the site because of snowdrifts. The dry weather operation costs were much lower than the wet weather costs. During dry weather one rotatiller could incorporate the total daily sludge production. Six D-8 Caterpillers were required to mix the total sludge production under the wet weather operations.

Recognizing that the FDI units could not be modified and operated to comply with the Colorado air pollution standards, Metro in 1971 revised the land application operation to provide for a continuous year-round disposal of the total sludge generated. For this purpose, Metro received permission to use an additional 259.2 hectares of pasture land at the LBR from the City and County of Denver.

Based on the experiences during 1969 and 1970 with the land application of sludge, several changes in sludge application methodology were adopted. Metro purchased the equipment necessary for the land application system, and utilized District personnel to operate this equipment. The method of operation consisted of transporting the filter cake from the treatment plant to the LBR in the same type of vehicle used in the previous operation. These vehicles were equipped with special seals to prevent accidental leakage during transport. A ramp was constructed at the application site which allowed the transport vehicles to transfer the sludge directly into spreaders. The 10 cubic meter farm manure spreaders were sized to accommodate one truckload of sludge. The spreaders were modified with special seals to handle the relatively wet vacuum filter cake to keep the sludge from flowing onto areas where it was not desired (Fig. 3). Special lighting was provided at the ramp to allow for operation 24 hours per day with two spreaders and one tractor. A standby tractor was rented for the purpose of allowing the primary unit to be serviced; thus, enabling operations to continue 7 days a week. Sludge was spread onto the surface of the grass and usually dried within one-half hour after application. After each application of 6.7 dry metric tons per hectare a spike tooth harrow was used to break up any large particles into fine particles. Cattle continued to graze the pasture during this operation.

In 1971, 115 hectares of the 260 hectares acquired earlier were used for sludge application. A total of 8,539 dry metric tons of solids were applied to the site resulting in a loading of approximately 74 dry tons per hectare. Soil and surface water monitoring during 1971 indicated that there had been

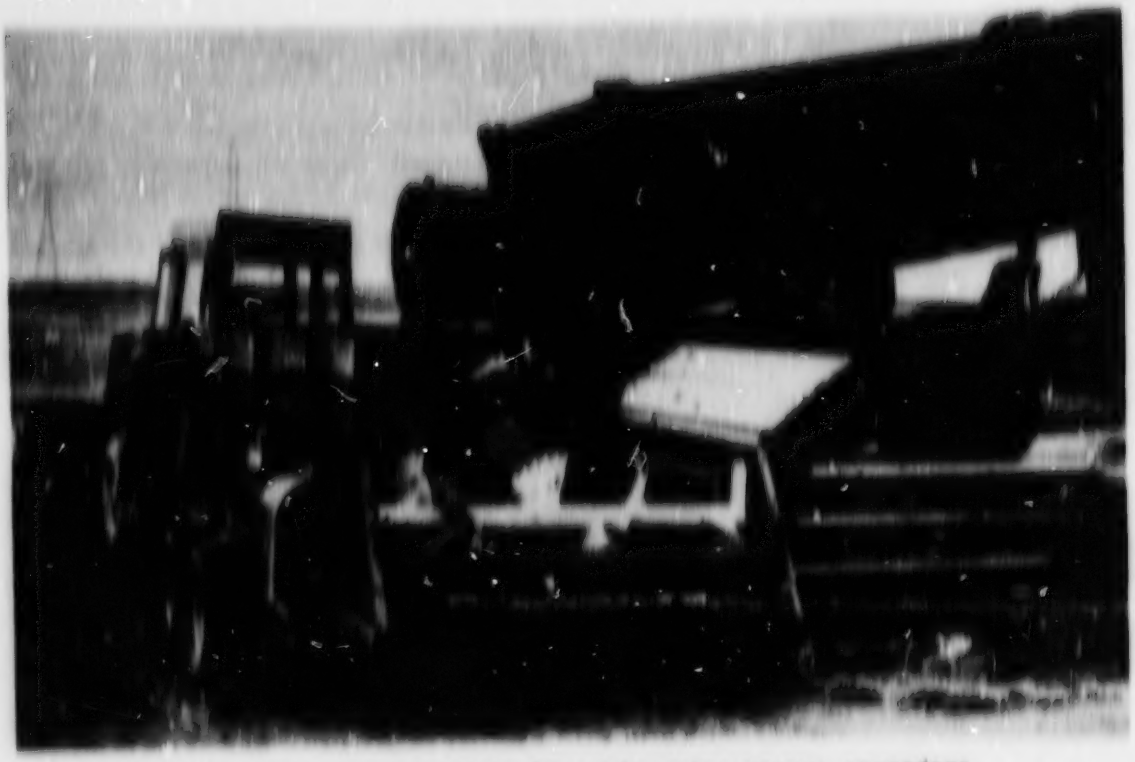

Fig. 3-Sludge being transferred to 10 cubic meter manure spreaders.

no contamination as a result of Metro's operation at this site. A major advantage of this method was that the operation did not disturb the native vegetation. Based on visual observations the vegetative production at this site improved compared to the surrounding area that did not receive sludge applications. Another major advantage of this operation was that it was far less expensive than the incinerator drying operation (Table 1). This method was also environmentally acceptable from the standpoint of soil conservation, air pollution and odor problems.

At the direction of the District Board of Directors, in November of 1972 Metro entered into a two year contract with a private contractor, Landfill, Inc. to provide services for land application of sludge utilizing the same technology which Metro staff had developed. Concurrently, Metro acquired an additional 200 hectares of land from the City and County of Denver for a total of 583.2 hectares.

The contractor utilized larger transport vehicles, 30 cubic meter units, and constructed a large sludge storage hopper to store sludge from the transport vehicles until it could be transferred into the spreader trucks (Fig. 4). The spreaders used by the contractor were also larger (15 cubic meters) than those used during the previous operation (Fig. 5). Each spreader was mounted on a large truck chassis previously used in open coal pit mining (23,622 kilogram rear axle capacity). The farm fertilizer spreaders were modified to

Table 1-Comparison of incinerator versus land application sludge disposal costs (1971)

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Fig. 4-Transport vehicle dumping into sludge storage hopper.

Fig. 6-Modified fertilizer spreader spreading sludge.

handle the relatively wet filter cake. During the fall and winter of 1971 and 1972 the contractor spread the sludge thinly over the grassland. In early spring of 1972 the contractor experienced difficulty with access to the field. As a result, large quantities of vacuum filter cake were stockpiled to a depth of 1.2 meters in a depression near a dry stream bed on the site. After completion of the stockpiling of filter cake, snowstorms occurred which covered the stockpiled filter cake. Metro inspectors were unaware of the unauthorized modification of the method previously agreed upon. As the snow began to melt, the stockpiled sludge began to decompose creating odor nuisances to people living in the area adjacent to the site. During late spring when the area had dried, small smoldering fires started in the areas which had received many consecutive sludge applications, a result of careless smokers and heavy equipment operating in the area. The smoldering fires were difficult to extinguish particularly during high winds.

Complaints to the Arapahoe County Commissioners made by residents living in the adjacent area resulted in a Public Hearing on June 20, 1972. At the Public Hearing Metro proposed a new method of land application to eliminate the odor and fire hazards previously experienced. This proposal was approved by the County Commissioners and implementation began in June of 1972.

Fig. 6-Mold board plow incorporating sludge.

The revised method consisted of applying the filter cake to the land at a depth of 5 to 8 centimeters (approximately 74 dry metric tons per hectare), and within six hours of application incorporating the sludge to a depth of 20 centimeters using a 41 centimeter mold board plow or a 76 centimeter disc plow (Fig. 6). After sludge incorporation the soil was tilled with an offset disc several times until a suitable seed bed had been prepared. As the native vegetation is disturbed by this method the soil is seeded with wheat or other forage crops such as sudan or oats to provide a vegetative cover to protect the soil from wind and water erosion. Because germination is inhibited if the soil is seeded immediately after sludge incorporation, the soil is allowed to set or incubate for 2 months before seeding. With the assistance of the Soil Conservation Service staff a plan was developed to establish permanent contours on the entire application site. One or more crops are raised each year to provide food for the grazing cattle and to reduce soil erosion.

Since 1972 this method has been providing satisfactory control of the odor and fire problems previously experienced. While this method is satisfactory during dry weather, special modifications had to be adapted during winter operations. In the fall of 1972 an additional 260 hectares were acquired for the expressed purpose of inclement weather incorporation. The sludge was

spread on the land by tilling to a depth of 60 centimeters and intermixed with the soil at a ratio of five parts soil to one part sludge. Since 1973 the inclement weather site has been prepared in advance by bench and terracing the area. Sludge loadings to the inclement weather site have exceeded 670 dry metric tons per hectare per year. Each inclement weather site is loaded only once. Inclement weather application generally takes place during December, January and February depending upon the severity of the winter. During the relatively mild, dry winter of 1974-1975 the inclement weather site was required for only 30 days during January and February.

EVALUATION OF SLUDGE EFFECTS ON THE LOWRY BOMBING RANGE

TYPE OF SLUDGE

If sewage sludge is to be utilized as a soil conditioner or fertilizer, parameters such as nutrient content, metals, conductivity, pH and organic matter should be known in order to evaluate effects on subsequent plant growth. When sludge is applied to soil, one of its immediate benefits is its N (nitrogen) and P (phosphorous) content. Because much of the N is tied up in the organic fraction it becomes a valuable source of slow release N. In addition to macro-nutrients such as N and P, sludge is a valuable source of micro-nutrients such as Zn (zinc), Cu (copper), B (boron) and Mo (molybdenum) when applied at low rates. The stable organic matter contained in sludge becomes a benefit by acting as a soil conditioner, which increases soil CEC (cation exchange capacity), water holding capacity, infiltration rates and the general tilth of the soil.

Potential problems that could arise from heavy applications of sewage sludge include inhibition of germination from excess salts, phytotoxicity from heavy metals, excess N and P, pathogens, and odors.

The sludge sources that comprised the vacuum filter cake incorporated into the soil at the LBR included:

A) Raw primary sludge - 40% of total.

B) Waste activated sludge - 45% of total.

C) Anaerobically digested primary sludge - 15% of total.

This sludge mixture was dewatered by applying FeCl3 (6-12% of dry weight) and slaked lime (20-30% of dry weight). In the fall of 1973, cationic polymers were substituted in part for the FeCl3 and lime. The amount of polymer required (4.5 to 6.8 kg/0.9 metric ton dry weight) was insignificant compared with the approximate 30% chemicals added to the vacuum filter feed when FeCl3 and lime were applied. Thus, the polymer conditioned vacuum filter cake represents the average chemical composition of the sludge without chemicals. Summarized in Table 2 are the arithmetic means and standard deviations for all of the chemical constituents analyzed in both types of vacuum filter cake for the years 1972 through 1975.

Major differences between the two types of filter cake are as follows:

1. pH: FeCl3 and lime cake = 11.4 versus 6.6 for polymer cake.

Table 2-A comparison of chemical composition of ferric chloride and lime treated vacuum filter cake with polymer conditioned vacuum filter cake (1972-1975 data)

Analysis	Units	Vacuum filter cake w/ferric & lime Mean	Vacuum filter cake w/ferric & lime ± S.D.*	Vacuum filter cake w/polymer Mean	Vacuum filter cake w/polymer ± S.D.*
pH	Units	11.4	0.9	6.8	0.8
Volatile fraction	% of TS	54.9	6.2	69.6	5.6
Conductivity	µmho/cm	9,790	3,087	4,820	1,820
Ag	mg/kg-dry wt.	51	22	"	"
As	"	17	"	"	"
B	"	53.5	12.0	"	"
Ba	"	440	141	"	"
Bi	"	10	"	"	"
Ca	"	87,300	26,720	21,800	11,690
Cd	"	18.9	14.2	18.8	10.4
Co	"	77	32	"	"
Cr	"	480	262	711	366
Cu	"	770	295	924	234
Fe	"	34,160	9,330	7,120	2,860
Hg	"	4.7	3.8	"	"
K	"	4,800	"	"	"
Li	"	20	"	"	"
Mn	"	355	160	215	112
Mo	"	19.3	7.9	"	"
N (TKN)	"	38,640	8,230	56,415	11,930
Na	"	6,300	"	"	"
Ni	"	290	195	344	132
P	"	16,700	5,400	21,870	10,700
Pb	"	491	312	588	199
Se	"	7	"	"	"
Sn	"	135	17	"	"
Sr	"	310	128	"	"
Ti	"	1,075	208	"	"
U	"	8	"	"	"
V	"	70	"	"	"
Y	"	55	8	"	"
Zn	"	1,805	719	1,864	854
Zr	"	153	58	"	"

* Standard Deviation

2. Percent volatile solids: $FeCl_3$ and lime cake = 54.9% versus 69.6% for polymer cake.

3. Electrical conductivity (μmho/cm): $FeCl_3$ and lime cake = 9,790 versus 4,820 for polymer cake.

4. Calcium: $FeCl_3$ and lime cake = 87,380 ppm versus 21,800 ppm for polymer cake (dry weight basis).

With regard to plant nutrients, the high pH of the $FeCl_3$ and lime treated sludge resulted in significant losses of volatile ammonia (NH_3), as was evident by the strongly pungent NH_3 odors prevalent in the vacuum filter process building during treatment with $FeCl_3$ and lime. Although dilution of the filter feed with chemical may have accounted for part of the reduction in N concentration (from 5.67% N in polymer cake to 3.86% N in $FeCl_3$ + lime cake) the 32% loss in TKN (total Kjeldahl nitrogen) was in great part due to NH_3 volatilization. The 22% reduction in P concentrations is attributable to the dilution effect with additions of $FeCl_3$ and lime.

Average sludge loadings have been at the rate of 67.2 metric tons/hectare/-year which would mean that approximately 2,600 kilograms of N/hectare/year have been applied with the addition of $FeCl_3$ and lime cake compared to 3,800 kilograms of N/hectare/year for the polymer cake. Sludge has been applied annually to much of the area since 1969; thus, N has been applied far in excess of crop needs.

SOIL EFFECTS OF SLUDGE DISPOSAL AT THE LOWRY BOMBING RANGE

The LBR sludge and disposal area is located east of Denver in Arapahoe County, Colorado. The county has a warm, semi-arid climate that is typical of the High Plains; thus, rainfall averages 35.6 centimeters, while the average annual temperature is about 10°C.

The dominant soils at the LBR are the Fondis and Renohill series. The Fondis soils are deep well drained soils located on uplands, and formed from loessal deposits overlying the Dawson formation (Pleistocene Age) (1). The Fondis surface soil is about 10 centimeters thick, free of lime, very dark grayish-brown and silt loam to silty clay loam in texture. The subsoil is 102 to 114 centimeters thick, contains free lime, dark yellowish brown and silt loam to clay in texture. The Fondis soils have moderately slow permeability, slow internal drainage and high available water holding capacity. The Renohill series which has developed on the Dawson formation is a moderately deep well drained soil (1). The surface layer is about 10 centimeters thick, free of lime, and is a dark brown loam. The subsurface soil is approximately 63 centimeters thick, contains free lime, dark brown to dark yellowish brown in color, and ranges from a loam to silty clay loam in texture. Renohill soils have medium internal drainage, moderately slow to slow permeability and moderate water holding capacity.

Starting in 1972 an attempt was made to monitor and evaluate the degree of possible soil pollution from excessive salts or heavy metals after continuous sludge applications. A general survey, which examined a number of soil cores

to a depth of 0.9 meters was taken semi-annually. Soil samples, which represent only one sample point from each area, were analyzed for pH, conductivity, nitrate nitrogen (NO_3-N), ammonium nitrogen (NH_4-N), sodium bicarbonate extractable P, ammonium acetate extractable K, chlorides (Cl) and diethlenetriamine-pentacedic acid (DTPA) extractable Zn, Fe, Cu and Mn (see Appendix A).

Site 1 was a control area, while sites 2 through 7 were areas that had received varying amounts of sludge (see Fig. 7).

Soil samples collected in November of 1974 had total sludge loadings varying from 0 to 545 metric tons/hectare. Heavy metal analysis and pH for surface soils (0 - 15.24 cm) from the November 1974 sampling are shown in Table 3. Subsurface soils are not included in the table since there was no apparent leaching of metals below the surface (see Appendix A for subsoil analysis).

Table 3-Concentrations of DTPA extractable Zn, Fe, Cu, Mn and pH from sludge additions to surface soils (0-15.24 cm) at the Lowry Bombing Range[a]

Site #	pH	Zn	Fe	Cu	Mn	Estimated tons of sludge applied/hectare (dry wt.)
1A	7.5	0.8	8.0	0.7	13.7	0
1B	7.6	0.6	6.0	0.6	8.0	0
1C	8.1	0.8	16.0	0.7	16.0	0
2A	7.5	10.5	20.0	0.4	17.0	24
2B	7.6	10.2	21.6	0.8	8.5	24
2C	7.8	16.0	17.3	0.6	10.0	100
3A	7.1	41.5	89.0	17.5	16.5	165
3B	6.4	93.0	85.7	15.6	96.0	165
3C	7.7	16.0	62.0	12.5	89.0	165
4A	7.6	56.0	87.0	35.0	51.0	184
4B	6.6	19.0	64.5	6.5	34.0	198
4C	7.3	8.3	24.4	5.7	15.0	202
5A	7.8	83.0	8.0	4.6	85.0	287
5B	7.1	28.0	68.0	12.6	60.0	551
5C	7.3	14.5	30.5	7.4	15.0	581
6A	7.8	45.0	71.0	42.0	16.0	681
6A	7.5	68.0	78.0	18.0	8.0	545

[a]Soils sampled in November 1974.

The concentration of the various chemical constituents examined did not reflect the estimated sludge loadings to each site, thus, it can be concluded that the sludge application is extremely variable, or that the sludge soil mix is not adequate.

An examination of data from site 5C demonstrates the extreme heterogeneity of the sludge-soil mix within one field. Analysis of a soil sample taken in May of 1974 is compared with the analysis of a soil sample from the same field collected in November of 1974 (Table 4). There were no sludge applications to

Fig. 7-Lowry Bombing Range sludge recycle site showing sample areas used for soil monitoring program. Shaded areas represent fields to which sludge has been applied.

this field between these sampling dates. None of the chemical constituents examined are similar.

Table 4-Comparison of chemical constituents of soil samples from site 6C sampled in May 1974 and November 1974

Analysis	Units	May 1974	November 1974
pH	units	7.4	7.6
Conductivity	mmho	3.6	15.4
Zn (DTPA)	mg/kg	.95	85.0
Fe (DTPA)	mg/kg	6.2	8.8
Cu (DTPA)	mg/kg	1.47	4.0
Mn (DTPA)	mg/kg	8.50	85.0
NO_3-N	mg/kg	240.0	1000.0
NH_4-N	mg/kg	12.0	11.0
TKN	%	0.31	0.52
P	mg/kg	385.0	450.0
K	mg/kg	358.0	480.0

The range in DTPA extractable metal content for Zn (See Table 3) is from 0.6 ppm in the control to a high of 85.0 ppm at a 267 metric ton/hectare application, while Cu ranges from 0.6 ppm in the control to 42.0 ppm at a 461 metric ton/hectare application. It is interesting to note that the soil sample from site 6C (November 1974 sampling) apparently had the highest loading of sludge, as can be seen from the high Zn, Mn, N, P and conductivity levels (see Tables 3 and 4); however, the concentration of DTPA extractable Cu is quite low. The low extractability of Cu in this sample is probably a reflection of the high absorption or chelating capacity of the organic matter for Cu. Whether this statement is true is unknown since the total metal content of the soil samples was not determined. However, this example tends to point out the fallibility in trying to analyze the toxic metal status of a soil when employing an extraction technique which only examines some fraction of the total metal present. Whether the levels of metals encountered in this survey (many of which are relatively high) could produce phytotoxic effects on the plants growing on these soils is unknown, since plants growing on these sites were not collected for analysis of metals, nor were yield determinations made. It can only be noted that the wheat crop growing on these sites appeared to be healthy.

Soil pH at the Lowry Bombing Range naturally ranges from about 7.0 to 8.0. Sludge additions had little effect on lowering the soil pH, which reflects the saturation with calcium carbonates in these soils.

Soil conductivity shown in Table 5 is like the metal data, extremely variable,

ranging from a low of 0.5 mmho/cm in the control area to a high of 15 mmho/cm at site 5C. About one-third of the sites with sludge applications showed conductivity levels from 4 to 14 mmho/cm which could be considered injurious to some of the crops grown in this area.

Table 5-Concentrations of NO_3-N, NH_4^+-N, TKN, P, K and conductivity from sludge additions to surface soils (0-15.24 cm) of the Lowry Bombing Range

Site #	mg/kg (dry wt.) NO_3-N	mg/kg (dry wt.) NH_4-N	% TKN	mg/kg (dry wt.) P	mg/kg (dry wt.) K	mmho Conductivity	Estimated tons/ha applied (dry wt.)
1A	1	21	.116	22	393	.6	0
1B	1	14	.159	4	525	.5	0
1C	1	10	.070	17	265	1.1	0
2A	2	12	.174	80	650	1.2	74
6A	46	20	.136	125	425	1.8	74
6B	32	20	.145	175	342	1.4	130
3A	570	32	.292	365	700	8.7	143
3B	600	30	.230	325	1060	9.2	143
3C	400	10	.242	225	700	1.7	143
4C	330	9	.280	440	500	6.8	184
2C	435	47	.197	120	405	8.7	195
2E	6	10	.150	72	393	.9	802
5C	1000	11	.520	450	490	15.4	267
4A	220	19	.219	164	418	.9	393
4B	160	83	.162	115	405	2.8	561
5B	300	22	.297	345	363	4.1	461
5A	680	32	.341	450	363	8.5	542

Soils in this area are naturally high in K and rarely require any K fertilization for crop production. The addition of sludge has increased the extractable K levels in all cases (see table 5), but not to a detrimental level.

Sludge applications have increased the available P content to high levels (see table 4), but it is doubtful that these levels are detrimental to crop growth since there is a more than adequate supply of available Zn, Cu, Mn and Fe which would tend to offset any P induced Zn, Cu, Mn or Fe deficiencies.

Two factors play a role in the extreme variability of N content of the sludged soils at the LBR. The first factor is the extreme heterogeneity of the sludge-soil mixture which has already been noted. The second factor is that the sludge itself is extremely variable. From table 1 it can be seen that the dewatering process used at the treatment plant ($FeCl_3$ + lime versus polymer) will affect the N content of the sludge; thus the average N content of the sludge varies from about 3% to 6%.

Continuous sludge applications since 1969 have increased the N content of the soil (see Table 6) to excessive levels, beyond any capacity for crop removal. Immediately available N (NO_3-N + NH_4-N) ranges from a low of 31.4 kilograms per hectare at site 2A to a high of 1132.3 kilograms per hectare at site 6C. If only 3% of the TKN becomes available for plant uptake during the growing season, then site 2A contains a total of 135.4 kilograms per hectare of available N while site 6C contains 1444 kilograms per hectare. Because of these high rates, N has leached below the rooting zone. Summarized in Table 6 are NO_3-N, NH_4-N and TKN data for the 61 to 91 centimeter depth. The leaching rates do not appear to be excessive, and it is doubtful that NO_3 from sludge applications would ever pollute the ground water. Rainwater in this area is insufficient (approximately 36 centimeters per year) to percolate to any significant depth, and potable water is from 100 meters to 300 meters deep which is protected by impervious stratum within the Dawson formation.

Table 6-Concentrations of NO_3-N, NH_4-N and TKN from subsurface soils (61 to 91 cm depth) at the Lowry Bombing Range

Site #	ppm NO_3-N	ppm NH_4-N	% TKN	ppm P	Estimated tons/ha applied (dry wt.)
1A	1	7	.029	< 3	0
1B	1	15	.028	3	0
1C	19	6	.024	27	0
2A	6	10	.031	3	74
6A	1	15	.024	8	74
6B	3	15	.022	25	190
3A	49	7	.043	15	143
3B	33	7	.043	8	143
3C	28	13	.060	5	143
4C	54	9	.034	23	184
5C	3	11	.036	3	198
5B	1	7	.027	10	202
5C	21	14	.050	3	287
4A	3	19	.033	20	359
4B	25	21	.034	8	381
6B	21	19	.030	5	461
5A	21	19	.039	8	542

Grab samples of soil and leaf tissue from winter wheat (Wichita) were collected from the LBR on May 31, 1974. Results of total metal analysis are shown in Table 7. The plant and soil samples were digested in a nitric-perchloric acid mixture and metals determined using atomic absorption. The plant samples were not washed prior to analysis, nor was background correction applied during the analysis of Cd, Pb or Ni. However, none of the metal concentrations reported in Table 7 would be considered out of the normal elemental composition range for plant materials.

Table 7-Total metal composition of soil and wheat from the Lowry Bombing Range

	mg/kg (dry wt.)				
Site #	Zn	Cu	Ni	Cd	Pb
Soils:					
1	69	24	16	ND*	25
2	53	18	16	ND	22
3	105	40	25	.45	43
4	69	22	20	.35	20
5	60	25	20	.30	25
6	205	54	21	1.20	48
Plant tissue:					
1	15	5.6	5.5	.17	5.7
2	16	8.4	4.0	.12	3.4
3	23	10.6	4.5	.10	5.3
4	46	12.7	4.0	.41	1.3
5	58	15.4	5.5	.22	6.6
6	65	36.5	5.5	.34	5.2

*ND - not detected

RESEARCH AND DEVELOPMENT

By 1971, it had become apparent that land application of filter cake was not to be a temporary expedient in place of incineration, but a long term necessity. Metro staff therefore contacted the Agronomy Department of Colorado State University (CSU) at Fort Collins, Colorado to investigate the various aspects of sludge loading rates, as well as other conditions necessary for beneficial utilization of nutrients in sewage sludge.

The goals of this research effort included:

1. Investigation of alternative land application and incorporation methods.
2. Environmental monitoring of soil, plants, ground water and air.
3. Evaluation of various crops that could benefit from optimal loadings of sludge to soil.

The information from this research was to be made available to that segment of the farm community wishing to apply sludge to their land in the proper season and amount.

In 1971 a contract was signed with the CSU Department of Agronomy and Danford Champlin Farms for a 0.81 hectare research site at Watkins, Colorado to investigate the effects of various sludge loadings on plant germination and growth. Results from this experiment led to greenhouse experiments using a range of crops including millet, wheat and sorghum sudangrass hybrid. These crops were subjected to various sludge loadings and various incubation periods between sludge application and seeding.

On the basis of results obtained from these projects as well as recommendations of Metro's consulting engineers to utilize the semi-arid climate and evaporation capacity in Colorado for air drying, an investigation of air drying of anaerobically digested sludge in drying basins at the CSU agronomy farm at Fort Collins was initiated in 1973.

Obnoxious odors experienced during some of the early research work at Watkins led to investigation of various subsurface injection devices which would inject liquid sludge beneath the soil surface to avoid aesthetic and odor problems. Therefore, liquid sludge was injected into the soil at Watkins, Colorado. Two injection devices were used, one owned by Danford Champlin Farms and one designed by James Smith of CSU; both devices worked well and no odor problems developed when these devices were used.

LAND APPLICATION OF METRO SEWAGE SLUDGE AT WATKINS, COLORADO: EFFECT ON GROWTH AND CHEMICAL COMPOSITION OF PLANTS*

Objectives of the Study

1. To determine the maximum application rate of the Metro sewage sludge to the sandy soils of western Adams County, Colorado consistent with continued crop productivity without causing heavy metal, organic or pathogenic pollution of soil or water.

2. To determine the extent of leaching and/or accumulation of substances derived from sewage sludge applied to soil.

Materials and Methods

A field study was set up on a Truckton sandy loam soil in western Adams County. Soil characteristics before sludge application are shown in Table B. These are deep soils with loamy sand surface layers and loamy subsoils that grade into sand at depths of 50 to 76 centimeters. They are on terraces and uplands, and are developed from sandy alluvium washed from the arkosic sandstones to the south. Wind has reworked the sandy alluvium in most areas developing an undulating to rolling topography. About one-third of the area of this soil has slopes less than 3% and two-thirds is rolling and slopes an average 6%.

Table B-Characteristics of the Truckton loamy sand used in the study

% sand	% silt	% clay	Texture[a] class	cec[b] m.e./100 gm	Field infiltration rate cm/hr	o.m.[c] %
78	14	8	Loamy Sand	6.6	10.7	1.6

Extractable - ppm

NO_3-N[d]	P[e]	K[f]	Zn[g]	Cu[g]	Fe[g]	Mn[g]
8	10	150	2	1	10	10

a) Pipette Method, OM oxidized by H_2O_2, dispersed with Calgon.
b) Determined by the ammonium acetate described by Jackson.
c) Determined by the chromic acid method described by Jackson.
d) Determined by the phenoldisulfonic acid method described by Jackson.
e) Determined by the ascorbic acid method described by Watanabe et al.
f) Determined by the ammonium acetate method described by Pratt.
g) Determined by the DTPA method described by Lindsay et al.

*This research was conducted for Metro by B.R. Sabey and W. Hart of Colorado State University, parts of which were published by them in the Journal of Environmental Quality, 1975. 4:2:252:256.

Plots (3 meters x 9.6 meters) were prepared by leveling the areas and building levees around each individual plot sufficient to contain the applied liquid sludge. Measured quantities of sewage sludge (approximately 5% solids) were pumped from tank trucks onto the plots on May 18 and 19, 1971. An analysis of the sludge is shown in Table 9. The liquid sludge as applied was approximately 50% primary anaerobically digested and 50% aerobically digested sludge.

Five ratios of liquid sludge ranging from 0 to 40.6 centimeters in depth were applied to each cropping situation in a single application prior to seedbed preparation. Amounts of liquid sludge applied were equivalent to 0, 25, 50, 100 and 125 metric tons/ha (dry weight). Three cropping situations - fallow, sorghum sudangrass hybrid (sorghum bicolor x s. sudanense) CV. NB 280 S, and millet (Panicum miliacium L.) CV Leonard were initially used. Each treatment was replicated four times in a randomized block design giving a total of 60 plots. In addition to these 60 plots, 12 more plots received applications of filter cake sludge varying from 27 metric tons to 112 metric tons/ha (dry weight). Plot design layout with loading rates is shown in Fig. 8.

Table 9-Typical analysis of anaerobically and aerobically digested sewage sludge produced by Metropolitan Denver Sewage Disposal District No. 1

	Anaerobically digested primary sludge, total solids: 5.7%		Aerobically digested waste activated sludge, total solids: 1.3%	
Element	% Dry weight	mg/l Wet weight	% Dry weight	mg/l Wet weight
N (organic)[a]	2.8	1600	6.6	3700
P[b]	1.3	731	3.1	1800
K[b]	1.1	627	1.4	570
Ti[c]	0.18	104	0.16	90
Sr	0.021	12	0.016	90
Mn	0.006	90	0.005	70
Fe	1.7	970	1.8	990
Co	0.001	0.60	0.007	0.40
Al	0.024	14	0.026	11
Cu	0.13	74	0.03	180
Zn	0.40	228	0.48	211
Cr	0.002	1.1	0.003	1.3
Ni	0.001	0.6	0.002	0.8
Cr	0.027	90	0.023	10.1
F	0.010	6.7	0.003	1.8
Cr	0.001	23	0.014	6.7
Mo	0.000	0.6	0.001	0.40
Ag	0.007	4.0	0.011	4.8
Ca	0.003	1.7	0.005	90
Sn	0.000	11	0.014	7.0
Ba	0.17	97	0.020	97
Pb	0.17	97	0.001	91
U	0.002	1.1	-	-
As	0	0	0.002	0.80
Se	0	0	0.000	2.0

1. Typical historical analysis, mean of some determinations.
2. Quantitative analysis conducted by industrial laboratories, mean of two analyses.
3. Qualitative analysis conducted by industrial laboratories. Quantitative analysis by fluorescence x-ray spectrophotometry, mean of four analyses.

Fig. 8-Plot design layout with identification and loadings (dry metric tons per hectare) of each plot.

It was expected that the moisture in the sludge would soak into the soil causing the sludge to dry rapidly. However, it took considerably longer than anticipated (about 4 to 6 weeks) for the sludge to dry (the plots with the highest rates remaining moist longest). In the interim, there were distinct odor and fly problems which led to the conclusion that high rates of a mixture of anaerobically stabilized and waste activated sludge could not be applied to the soil surface and allowed to dry.

When the sludge had dried, it was mixed into the top 14.4 centimeters by rotatilling. Soil samples were taken during the last week of June at various depths down to 0.76 meters. A seedbed was prepared by tandem discing and the sorghum sudangrass and millet were planted on July 5, 1971 a date that was later than optimum.

A sprinkler irrigation system was installed to supplement rainfall. Adequate moisture was provided for seed germination and for the prevention of crusting. Irrigation of approximately 5.6 centimeters and 7.1 centimeters were applied on July 12-14 and July 21-23 periods, respectively. These irrigations were in addition to rainfall of approximately 3.81 centimeters during the month of July 1971.*

Germination and emergence counts on the sorghum sudangrass and millet plots were made on July 20, 1971. The counts were made on three rows each 0.6 meters long. These data showed poor germination but since it was too late to reseed and reseeding immediately would probably not have been much more successful, it was decided that the project would be extended by planting winter wheat in the fall.

The sorghum sudangrass was harvested on September 1, 1971 in spite of poor germination and two hail storms. The green and dry weight yields were determined. A separate random sample was taken from each plot, dried and finely ground for a total N determination. The millet was not harvested because of severe hail damage.

Soil samples were taken at various depths down to 2.4 meters on September 14 and 15, 1971 prior to tillage and seedbed preparation for the wheat crop. The soil samples were analyzed for NO_3-N, sodium bicarbonate extractable P, ammonium acetate extractable K, DTPA extractable Zn, Fe, Cu and Mn.

After harvest of the sorghum sudangrass plots, all the plots were disced and a seedbed for winter wheat was prepared. Wheat was planted on October 5 on all 72 plots. Wheat germination and emergence counts were made on October 15, 1971.

On November 30, 1971 a limited number of plots were sampled to a soil depth of 10.16 centimeters for bacterial counts. Numbers of total aerobic, total coliform, fecal coliform, and fecal streptococci bacteria were determined by dilu-

*The reported value is the average rainfall of the Denver WSO, Byers, and Ft. Lupton U.S. Weather Bureau stations for the month.

tion counts using a membrane filter technique with the following (Difco Laboratories) media for each group:

1. Total bacteria: M-plate count broth, 17 gm in 1000 ml of distilled H_2O. Autoclave 15 minutes (15 lbs. pressure and 121°C). Use 2.2 ml per absorbent pad. Incubated 18-24 hours.

2. Total coliform: M-Endo broth-MF, 48 gm in 1000 ml distilled H_2O containing 21 ml ethanol. Heat to boiling. Cool. 2 ml to each sterile absorbent pad. Incubate at 35°C for 24 hours.

3. Fecal coliform: M-FC broth, 3.7 gm in 1000 ml distilled H_2O. Add 1 ml of 1% rosolic acid in 0.2 N NaOH. Heat to boiling. Cool. Use 2 ml per sterile absorbent pad. (Cultures incubated by submerging in 44.5°C water bath for 24 hours.)

4. Total streptococci: M-Enterococcus Agar, 42 gm in 1000 ml distilled H_2O. Heat to boiling to dissolve completely. Disperse into petri dishes and allow to solidify. Incubate for 48 hours at 35-37°C.

During the fall of 1971 it was decided to omit irrigation during the spring of 1972. The wheat grew well in the spring until hot dry weather threatened to eliminate the wheat yields, whereupon the decision was made to irrigate to save the crop and obtain some yield data. However, yields had already been severely depressed.

The wheat was harvested on July 14, 1972 and yields determined. Some subsamples of the grain were separated and finely ground in a stainless steel Wiley Mill for determinations of total N, P, K, Ca, Mg, Zn, Fe, Cu, Mn, Pb, B and Cd. Total N was determined by macro-Kjeldahl digestion using Kel Pak #2 as a catalyst, and distillation into boric acid. Phosphorus determinations were made following nitric-perchloric digestion colorimetrically using ammonium vanadate and ammonium molybdate. Potassium, Ca, Mg, Zn, Cu, Mn, Cd and Pb were digested with nitric perchloric acids, diluted and read on an atomic absorption spectrophotometer. Boron was determined by dry ashing at 550°C with ash dissolved in 0.1 N HCl and color development with circumineasalic acid. The color intensity was read on a spectrophotometer.

Infiltration measurements were made on four adjacent millet plots (see Fig. 8) in late July of 1972. These were chosen because they are adjacent to one another; thus, eliminating as much as possible the effects of soil variations in the measurements. Six unbuffered ring infiltrometers were installed in each plot and the cumulative infiltration (up to 10.16 centimeters total application) was determined as a function of time.

Results and Discussion

After application of the sewage sludge on the bordered plots, it took almost six weeks for the sludge to dry at the soil surface. This resulted in an appreciable odor and fly problem until the drying was completed. The conclusion that this sludge (a mixture of anaerobic and aerobically digested sludges)

could not be judiciously applied to the soil surface was reached. The aerobically digested waste activated sludge was not sufficiently stable to prevent odor and fly problems.

Germination and emergence data for the sorghum sudangrass, millet, and wheat grown on the field plots are shown in Tables 10 and 11. It is apparent that increasing amounts of sewage sludge increased inhibition of germination and emergence of sorghum sudangrass and millet. However, when the wheat was planted some five months later, the factor causing germination and emergence inhibition had been eliminated or dissipated, even at the higher rates of sludge application. There were no significant differences between the controls and sludge applied plots on germination and emergence of wheat.

Table 10-Germination and emergence counts on July 20, 1971 for three rows, each 7.65 meters long

Sludge application rate metric tons/ha	No. of plants (mean of 4 reps.)	
	No. of plants each S. sudangrass	No. of plants (mean) Millet
0	132 a*	824 a
2	32 b	13 b
4	14 b	23 b
8	4 b	4 b
10	6 b	8 b

* These means followed by the same letter are not significantly different at the 0.01 level, using Duncan's Multiple Range Test.

Table 11-Wheat stand counts on October 15, 1971 for three rows, each 1.83 meters long

Sludge application rate metric tons/ha	No. of plants (mean of 4 reps.)	
	Previous fallow plots	Previous millet plots
0	548 a*	564 a
2	541 a	485 a
4	440 a	427 a
8	418 a	377 a
10	398 a	495 a

*These means followed by the same letter are not significantly different at the 0.05 level.

The harvested weights of the sorghum sudangrass grown on the sludge treated plots are shown in Table 12. The extremely low values are due to poor germination and hail damage. The yield variations are more likely to be a result of differences in germination and emergence than directly due to the sludge addition on subsequent plant growth. From visual observations, the individual plants grown in the high sludge application plots were not smaller than those of the check plots or lower application rates.

Table 12-Yield and nitrogen content of sorghum sudangrass as affected by sludge application rate.

Application rate metric tons/ha	Yield dry weight (kg/ha)	%N
0	410 a*	1.08 a*
25	387 a	3.08 b
50	209 ab	3.23 b
100	101 b	3.30 b
125	60 b	3.43 b

* Mean value of 4 replications. The mean values for %N followed by the same letter are not significantly different at the .01 level. The mean values for dry matter yield followed by the same letter are not significantly different at the .05 level. Both sets of data were analyzed using the Duncan's Multiple Range Test.

The N contents of the harvested sorghum sudangrass are shown in Table 12. There was nearly a three-fold increase in the nitrogen level of the sorghum sudangrass grown on the sludge treated plots compared to that of the check plots. There were no significant differences in N content of the plants grown on any of the sludge treated plots even though the mean values increased slightly with increasing sludge applications.

The 1977 wheat yields on the three sets of plots are shown in Table 13. On the previously fallowed plots there was not a significant difference in yield between the check plots and any of the sludge application rates except at 125 metric tons/ha. This high rate was the only one at which wheat yields were significantly lower than the check. The wheat yield picture was different on the plots that were originally planted to millet. The mean yield values at the 25 and 50 metric tons/ha ratios were significantly higher than the checks. The yields on the 25 and 50 metric tons/ha plots were also significantly greater than the 100 and 125 metric tons/ha plots. The wheat yield pattern on the sorghum sudangrass plots is similar to that of the millet plots, but there were no significant differences; thus, the application of sewage sludge (125 metric tons/ha fallow plots) significantly decreased the yield of wheat com-

pared to the check, whereas in two instances (25 and 50 metric tons/ha - millet plots), sludge application appreciably increased wheat yields.

Table 13-Effect of sewage sludge addition to Truckton loamy sand on winter wheat yields, 1972

Application rate metric tons/ha	Dry matter yield (kg/ha) Treatment in 1971			
	Millet	Sorghum sudangrass	Fallow	Means
0	777 a*	439 a	826 a	681
25	1290 b	973 a	800 ab	931
50	1184 b	902 a	428 ab	838
100	886 a	858 a	808 ab	518
195	320 a	619 a	254 b	398

* Mean values of 4 replications. Values followed by the same letter are not significantly different at the 0.05 level using Duncan's Multiple Range Test.

Chemical analyses of wheat grain grown on the 0, 25 and 100 metric tons/ha treated plots are shown in Table 14. The mean values for N, K, Ca, Zn, and Mn increased significantly in the wheat grown on the 25 metric tons/ha plots compared to the checks. The additional increase at the 100 metric ton/ha compared to the 25 metric ton/ha rate was not as great. There were no significant differences between any of the application rates for P, Mg, Fe, Pb, and Cd. There was a significant difference in Cu content of the wheat between the 25 and the 100 metric ton/ha plots. However, in no case was the content of any of the elements analyzed high enough to be outside the normal range of concentrations found in plant materials.

It should be pointed out that when these plots were prepared the land was leveled to facilitate the application of liquid sludge to level bermed plots. During the operation much of the topsoil was redistributed, thus, some plots contained little topsoil while others had topsoil added to them. This probably resulted in considerable variability within the plots. This variability in soil most likely contributed to the variability in the data obtained, decreasing or obscuring statistical significance.

Since there were no duplicates on the filter cake plots, a different type of statistical analysis had to be run. A polynomial regression analysis indicated a slight decrease in wheat yield with increased filter cake addition above 454 kilograms per plot, but the differences are not significant (see Fig. 9). It should be noted that the checks averaged 550-769 kilograms per hectare, which is considerably lower than any of the filter cake plot yields.

An 8.1 hectare dryland area in a typical wheat field on the Danford-Champlin

Table 14-Total elemental composition of wheat grain as influenced by rate of Metro sewage sludge addition.

Element	Sludge application rates dry metric tons/ha 0	25	100
% N	2.06 a*	2.89 b	3.10 b
% P	0.41 a	0.51 a	0.45 a
% K	0.41 a	0.49 b	0.62 b
% Ca	0.046 a	0.073 b	0.076 b
% Mg	0.143 a	0.149 a	0.156 a
ppm Zn	34.0 a	52.5 b	64.2 b
ppm Fe	38.3 a	45.9 a	46.5 a
ppm Cu	3.50 a	4.46 a	5.96 b
ppm Mn	37.2 a	77.0 b	83.6 b
ppm Pb	0.15 a	0.14 a	0.08 a
ppm B	0.90 a	1.31 ab	1.46 b
ppm Cd	0.07 a	0.16 a	0.19 a

* The mean values in each row followed by the same letter are not significantly different at the 0.05 level using Duncan's Multiple Range Test.

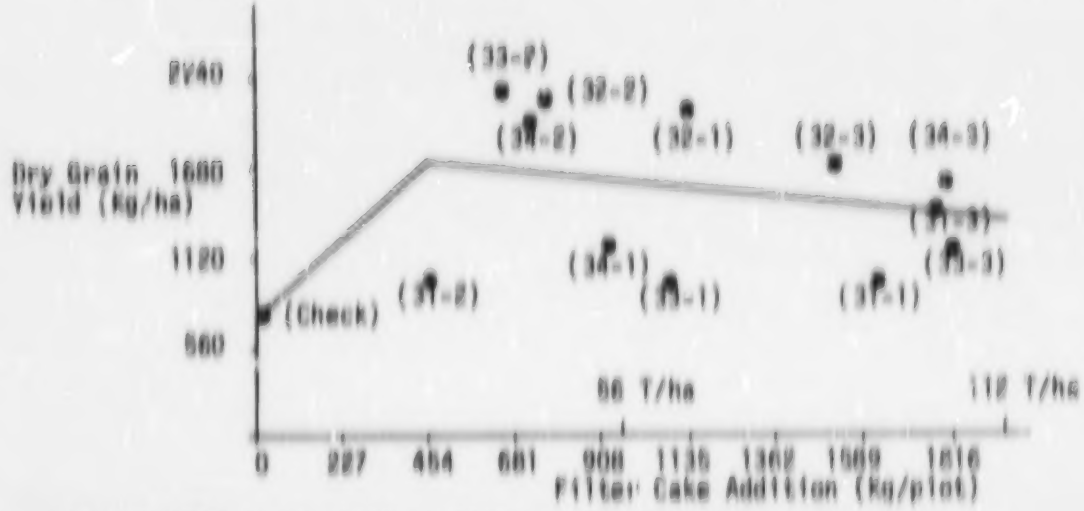

Fig. 9-1972 wheat yield on filter cake plots.

Farms at Watkins was treated with about 22.4 metric tons per hectare of filter cake during the summer of 1971. The cake was incorporated into the soil by tillage shortly after application. Winter wheat was planted and sampled on July 14, 1972. Five strips 1.2 x 15.2 meters were taken at random in the filter cake treated area and a similar sampling from the nonfilter cake treated area. The wheat yield data are shown in Table 15. There were no appreciable differences in the mean values of the filter cake treated and the nontreated strips.

Table 15-Wheat yields from applications of 22.4 metric tons per hectare of filter cake sludge

Dry matter yield (kg/ha)			
Sludge strips		Non-sludge strips	
	1602.0		2532.6
	1822.5		2279.16
	1613.4		1720.32
	3351.3		1646.1
	2502.0		1783.8
Mean	2042.2	Mean	1979.9

The field was harvested shortly after, and by a subjective evaluation of Mr. Jack Danford the yields were not greatly different on the two areas of the field. The filter cake had no apparent effect on dryland wheat yield.

There were no appreciable differences between the variation of the elements with soil depth as influenced by cropping situation. Therefore, results are discussed for all three cropping situations. Data which differ significantly from the general trends were eliminated for the generalized figures included in the text.

The first set of soil samples taken shortly after sludge incorporation showed the normal pH of the topsoil to be about 6.7 and increasing to about pH 7.0 at a depth of 0.76 meters, which is typical of soils in this area (see Fig. 10). After sludge incorporation the soil pH increased; however, after incubation through the summer months the pH of the surface soils (0 to 15 centimeters) decreased compared to the control plots.

Salt concentrations as measured by electrical conductivity show that the salt concentrations increased with increasing sludge additions (see Fig. 11). Sludge additions between 20 and 50 metric tons/ha did not cause a salt problem. Application rates greater than this caused the conductivity to rise to between 3 and 4 mmho/cm which could possibly be detrimental to sensitive crops.

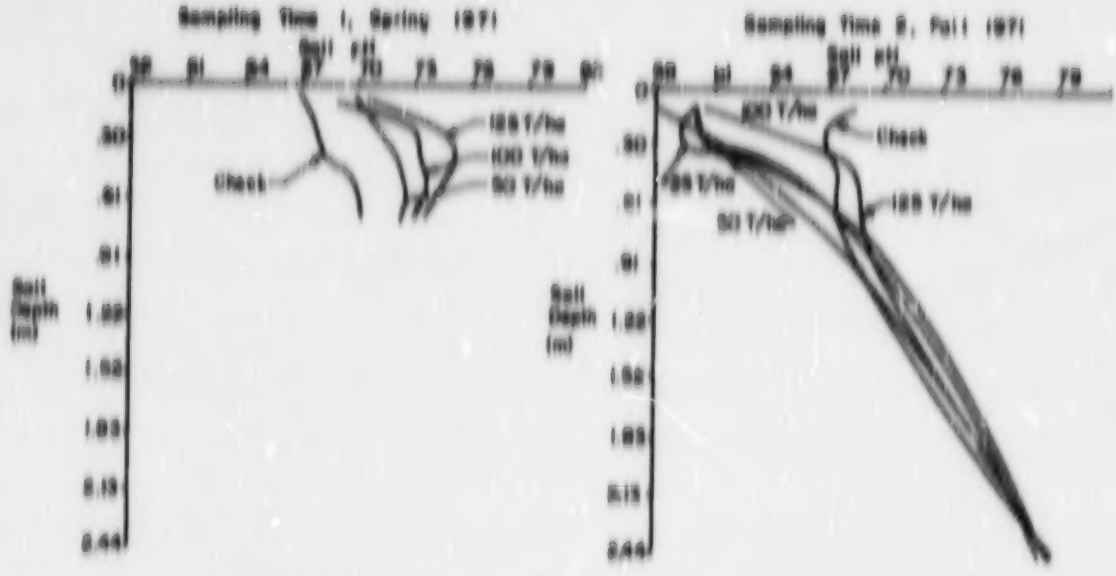

Fig. 10-pH of soil profile with various rates of sewage sludge additions.

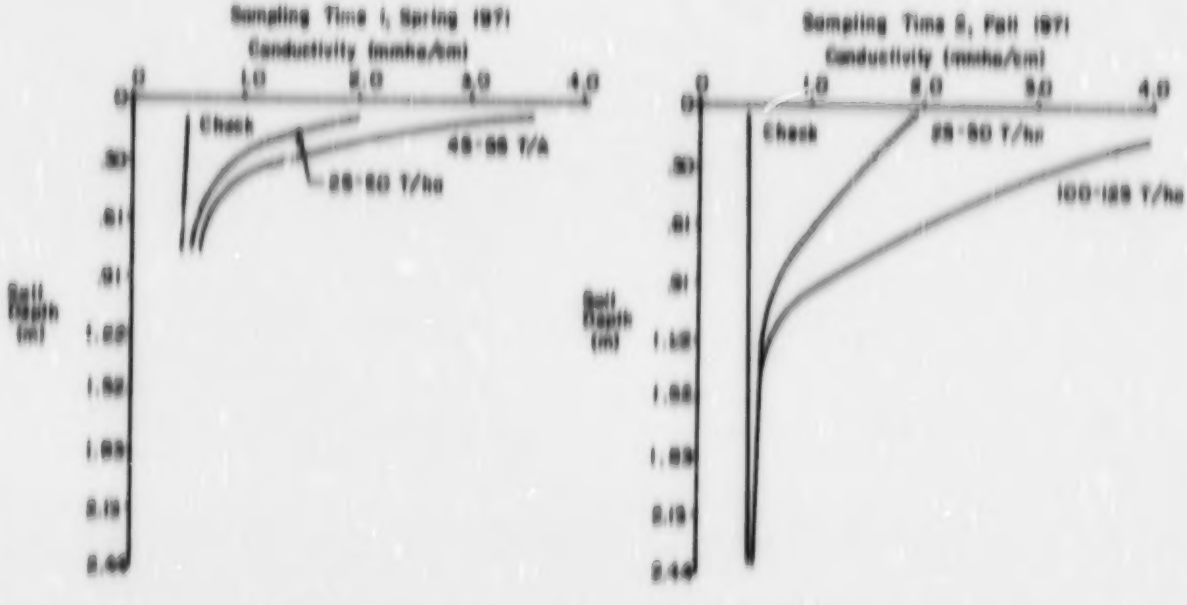

Fig. 11-Electrical conductivity of soil with various rates of sewage sludge additions.

The general change in organic matter content of the soil is shown in Fig. 12. The higher the sludge application rate the higher the organic matter content of the soil. Fig. 12 demonstrates that there was some organic matter decomposition during the summer months. Below the 0.3 meter depth there were no measurable differences in the organic matter content of the plots.

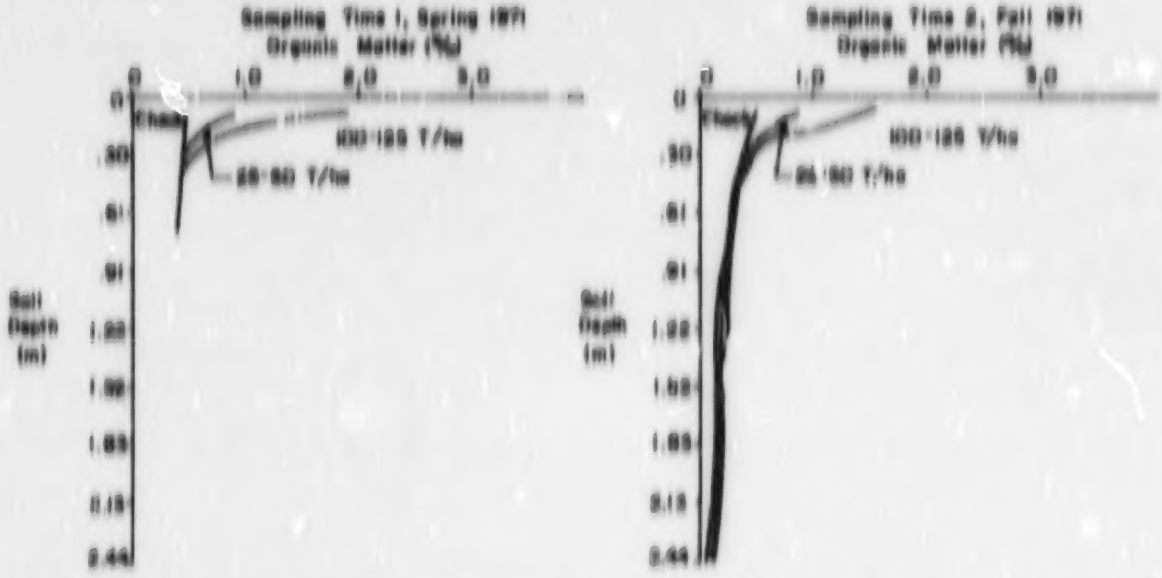

Fig. 12-Organic matter content of soil with various rates of sewage sludge additions.

Nitrate-nitrogen content of the surface soil samples were 2, 4 and 10 times higher than the control plots for the 25, 50 and 100 metric ton/ha sludge application rates, respectively (see Fig.13). The second sampling shows that the NO_3-N content had increased markedly in the surface soils and had leached to a depth of about 2 meters.

Available P remained for the most part in the surface soils with some movement to the 0.4 meter depth (see Fig.14). The bulge at the 1.5 meter depth is likely an analytical error rather than any movement to this depth. The surface soil samples that have had sludge applications all show high levels of available P, but it is doubtful that this could be considered detrimental to plant growth.

The check plots contained about 120 to 140 ppm of extractable K in the surface soils at the time of the first sampling (see Fig. 15). The intermediate sludge application rates (25 to 50 metric tons/ha) caused the available K level to increase to over 200 ppm. Heavy rates (100 to 125 metric tons/ha) caused the K content to rise to over 350 ppm. After the summer period, the K distribution had not changed appreciably in the surface soils. Sludge additions increased the K level to the 0.45 meter depth, possibly indicating some downward movement of K.

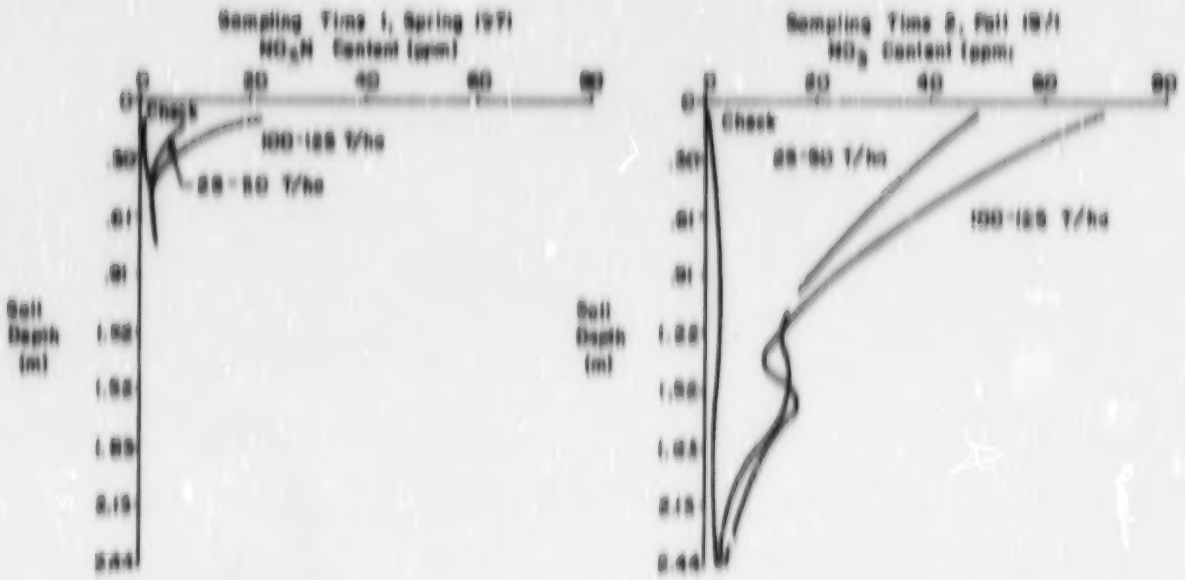

Fig. 13-NO_3-N of soil with various rates of sewage sludge additions.

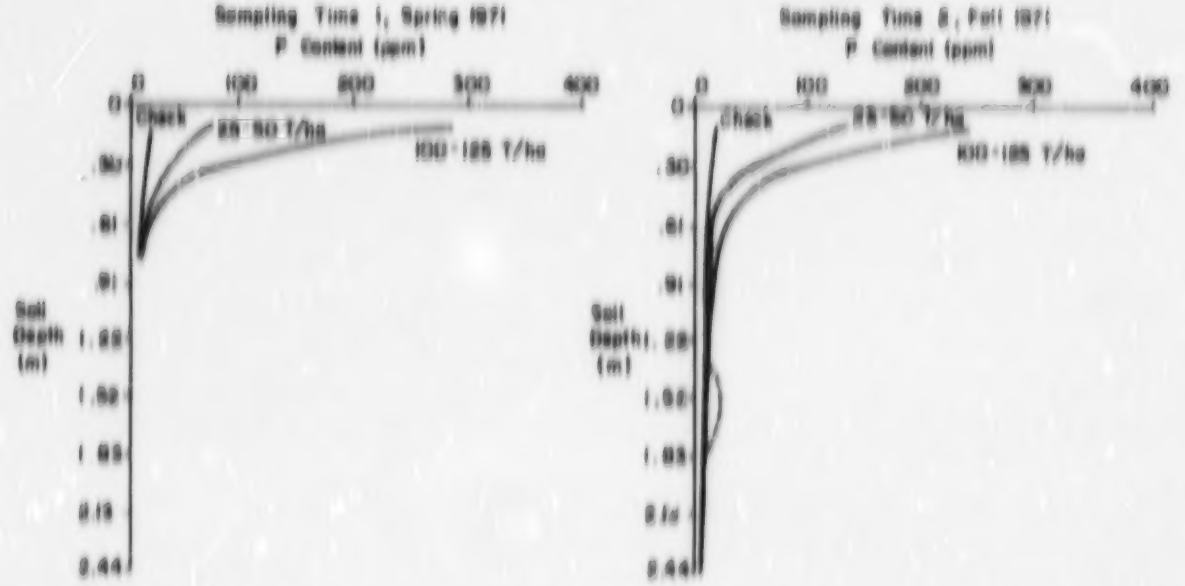

Fig. 14-Available P content of soil with various rates of sewage sludge additions.

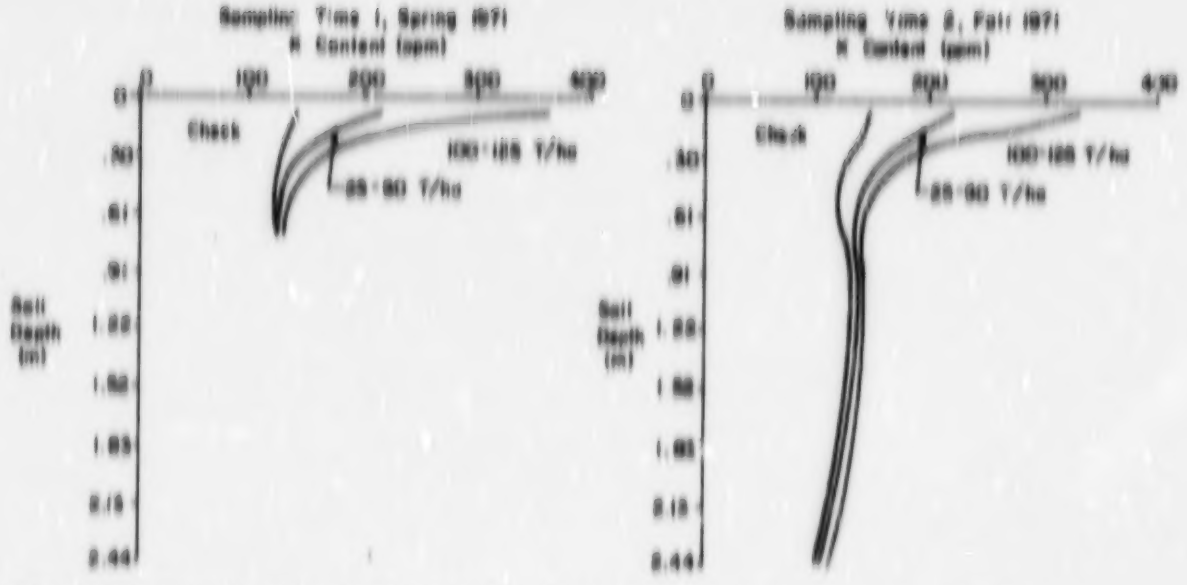

Fig. 15-Available K content of soil with various rates of sewage sludge additions.

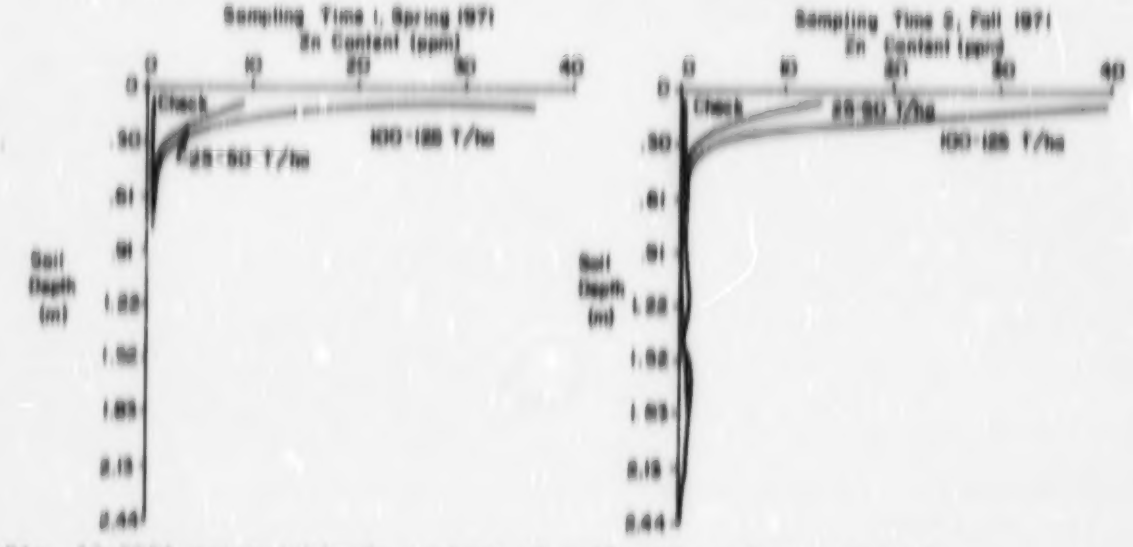

Fig. 16-DTPA extractable Zn content of soil with various rates of sewage sludge additions.

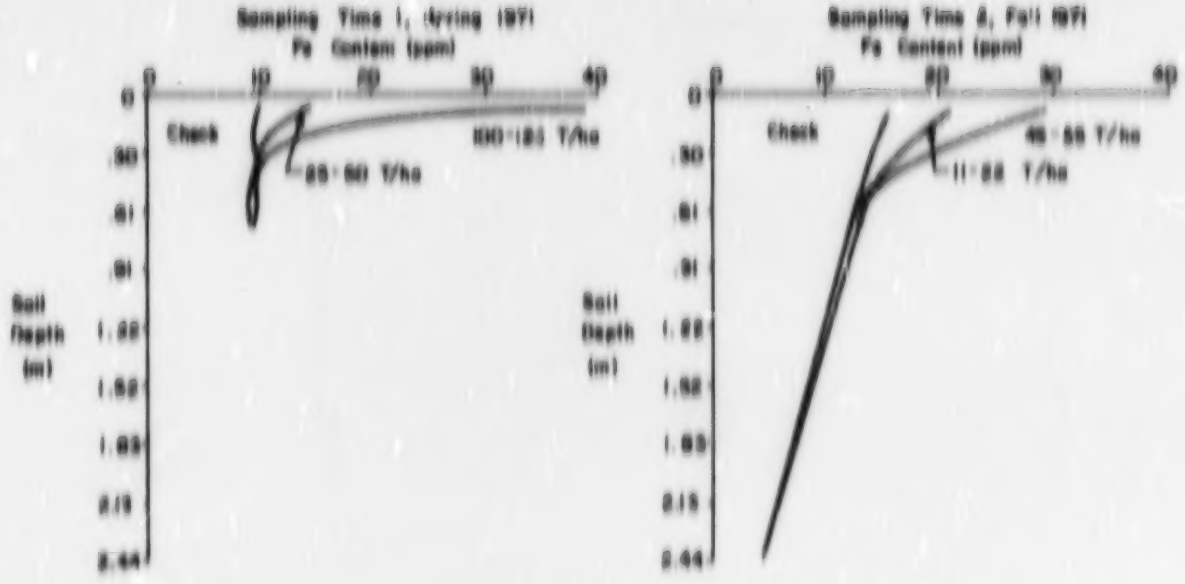

Fig. 17-DTPA extractable Fe content of soil with various rates of sewage sludge additions.

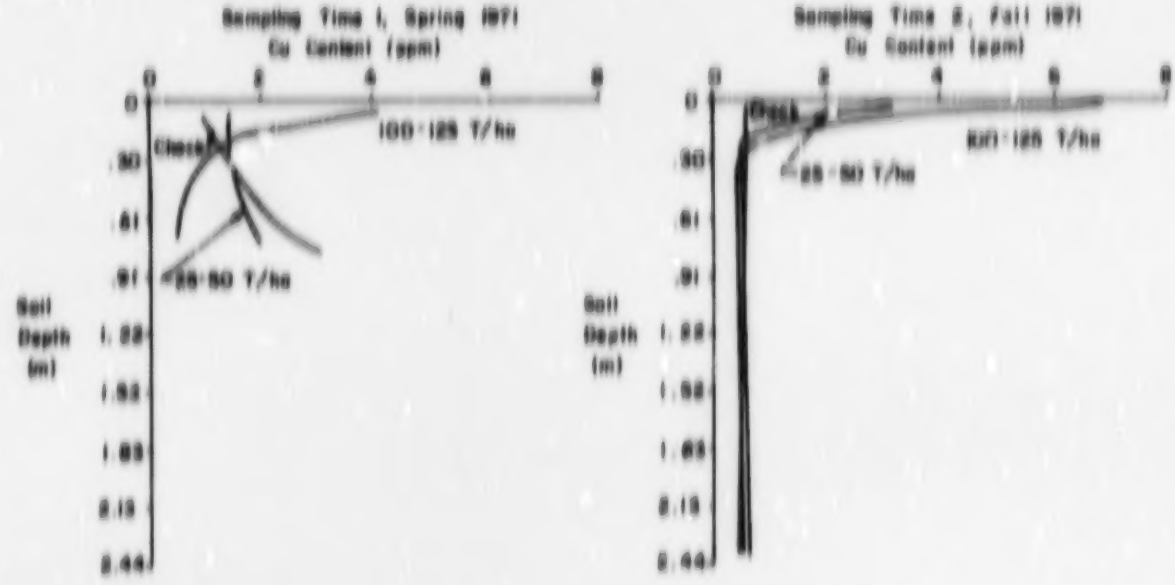

Fig. 18-DTPA extractable Cu content of soil with various rates of sewage sludge additions.

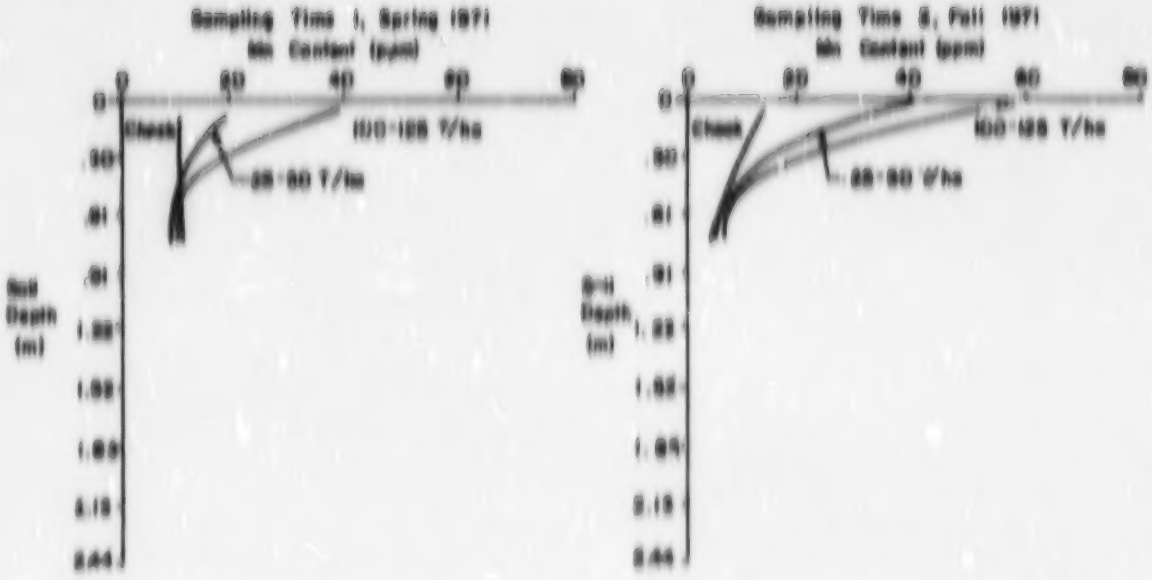

Fig. 19-DTPA extractable Mn content of soil with various rates of sewage sludge additions.

Bacterial counts were made on surface soil samples taken on November 30, 1971 after harvesting of the crops (see Table 16). There was an appreciable increase in total aerobic bacteria (probably reflects the increased food source of sludge organic matter), total coliform bacteria and fecal streptococci. Fecal coliform bacteria were not increased by sludge additions to the soil. An estimate of the number of fecal coliform bacteria in the original soil-sludge mixture would be on the order of 1 x 10^6; thus, the die off rate for fecal coliform during the summer months would be somewhere around a thousand to ten thousand fold.

Infiltration determinations were made on four adjacent millet plots (see Fig. 8) in late July of 1972. Twelve determinations made on the control plots were considered checks and those on the 125 metric ton/ha of sludge applied plots were considered as the treated plots. The time to infiltrate 1.27 centimeters, 2.54 centimeters, 5.08 centimeters and 10.16 centimeters of water were taken as the dependent variables. In addition to the amount of sludge applied, the moisture content to the 91.44 centimeter depth and the center of gravity of the moisture to the 91.44 centimeter depth were also considered as factors affecting infiltration. The infiltration results are displayed in Fig. 17 and the average values for the infiltrated depths are shown in Table 17.

The scatter in Fig. 20 is typical of measurements made with cylinder infiltrometers. This is due in large measure to the small area samples (45.72 centimeter diameter) and the corresponding large edge effects around the cylinder. These are due primarily to the shattering of the soil when the infiltrometer is driven into the ground.

Table 16-Bacterial counts of soil samples taken from fields (fallow and sorghum sudangrass) treated with sewage sludge

Sludge applied metric tons/ha	Soil depth (cm)	Total aerobic bacteria	Total coliform bacteria	Fecal coliform bacteria	Fecal streptococci
Fallow					
0	0 - 3.8	3.3×10^6	2.2×10^3	$\leq 1 \times 10^3$	$\leq 1 \times 10^3$
185	0 - 3.8	24×10^6	6.9×10^3	$\leq 1 \times 10^3$	$\leq 3.8 \times 10^3$
Sorghum sudangrass					
0	0 - 3.8	4.0×10^6	1.4×10^3	$\leq 1 \times 10^3$	$\leq 1 \times 10^3$
0	3.8 - 6.3	5.8×10^6	$.85 \times 10^3$	$\leq 1 \times 10^3$	$\leq 1 \times 10^3$
0	6.3 - 10.1	5.6×10^6	$.04 \times 10^3$	$\leq 1 \times 10^3$	$\leq 1 \times 10^3$
85	0 - 3.8	13×10^6	$.65 \times 10^3$	$\leq 1 \times 10^3$	13×10^3
85	3.8 - 6.3	12×10^6	2.6×10^3	$\leq 1 \times 10^3$	85×10^3
85	6.3 - 10.1	16×10^6	4.5×10^3	$\leq 1 \times 10^3$	89×10^3
185	0 - 3.8	14×10^6	30×10^3	$\leq 1 \times 10^3$	$.8 \times 10^3$
185	3.8 - 6.3	17×10^6	5.3×10^3	$\leq 1 \times 10^3$	8.5×10^3
185	6.3 - 10.1	4×10^6	0.5×10^3	$\leq 1 \times 10^3$	5.9×10^3

Table 17-Average values for infiltration rates on sludge treated soils

Infiltrated depth of water (cm)	Time to infiltrate on control plots	Time to infiltrate on sludge plots
	min	
1.27	1.48	0.57
2.54	4.66	2.69
5.08	14.62	12.76
10.16	46.02	60.57

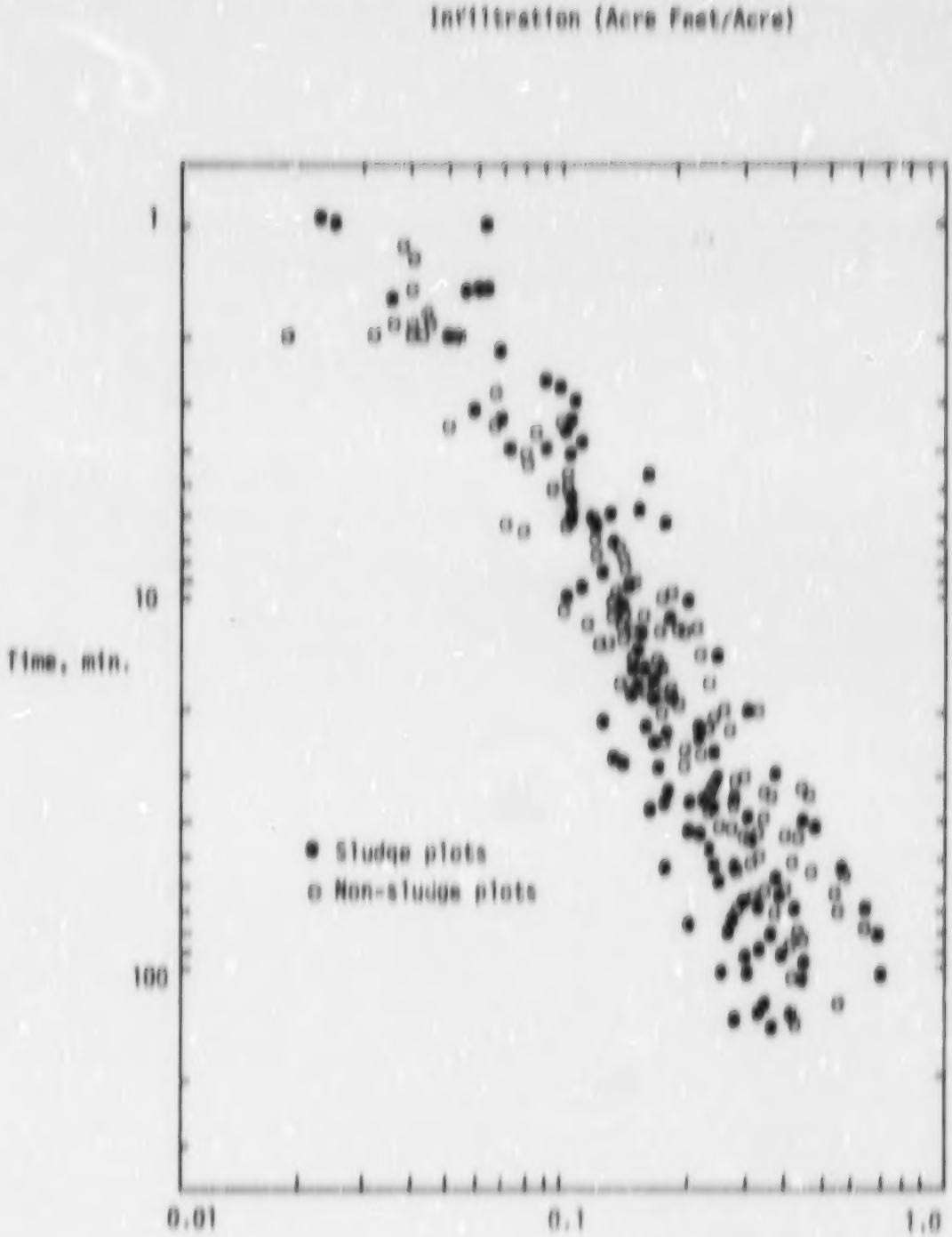

Fig. 20-Infiltration of water into sludge treated and non-sludge treated soils.

From the standpoint of modeling it was found that the effect of sludge application is largely overshadowed by other variables, except in the case of the ½ inch water application. The most significant variable found in modeling each of the water applications is shown in Table 18.

Table 18-Significant variables found in modeling water applications of 1.27, 2.54, 5.08 and 10.16 centimeters.

Depth of infiltrated water (inches)	Most influential variables measured
½	Moisture content, center of gravity of moisture content
1	Moisture content, center of gravity of moisture content, product of moisture content and center of gravity of moisture content
2	Moisture content, center of gravity of moisture content, sludge or sludge alone
4	None of variables selected were significant

The conclusion to be reached from the infiltration studies is that sludge did not appear to offer any adverse effect on the infiltration of water into the soil when measured after cropping.

Summary and Conclusions

Germination and emergence of the sorghum sudangrass and millet were poor on all plots where sludge had been applied. Subsequent poor growth and two hail storms prevented the obtaining of useful yield data. The winter wheat exhibited no germination or emergence inhibition. Wheat yield data showed a tendency toward increased growth on the 25 and 50 metric ton/ha sludge plots, but these increases were not statistically significant except for the original millet plots. When the plots were prepared the land was leveled to ensure level plots for the liquid sludge applications. This leveling caused some of the sandy topsoil to be removed from some areas and added to others. This resulted in considerable variability within the plots. This variability in soil most likely contributed to the variability in the data obtained, decreasing or obscuring statistical significance.

With increasing sludge applications there was an increase in salts, NO_3-N, P, K, Cu, Zn, Mn and Fe in the surface soil. Below the top 30 centimeters of soil only NO_3-N accumulated in appreciable quantities above the control levels. There was a slight indication of increased concentrations of P and K at 30 to 46 centimeter depths.

Microbial counts showed that the sludge plots had an appreciable increase in

total aerobic, total coliform and fecal streptococci bacteria, while the fecal coliform bacteria were not greater in the sludge plots than in the control plots.

Infiltration measurements indicated that infiltration was not significantly increased or decreased due to sludge application one year after application.

THE EFFECT OF METRO SLUDGE ON GERMINATION AND PLANT GROWTH OF THREE CROPS IN A GREENHOUSE STUDY

The studies conducted at the Watkins research plots demonstrated germination inhibition in sorghum sudangrass and millet when the seed was planted soon after liquid sludge incorporation into the soil. To investigate the effect of liquid sludge and filter cake on the rate of germination and subsequent early plant growth, a greenhouse study was conducted at the Elliot carnation greenhouse adjacent to the Metro plant.

Materials and Methods

A bulk sample of topsoil from the experimental area at Watkins, Colorado was obtained for mixing with raw sewage sludge and filter cake for this study.

Samples of typically produced sewage sludge and filter cake were dried and prepared for bulk mixing with the soil as shown in Table 19.

Table 19-Rate of sludge applications to Truckton sandy loam soil

Treatment no.	Sludge addition	Equivalent dry rates in metric tons/ha	Type of Sludge[a]
1	0	0	
2	1.0	22.4	Filter cake[b]
3	2.0	44.8	Filter cake
4	4.0	100.7	Filter cake
5	2.0	44.8	Dried[c]
6	4.0	100.7	Dried
7	8.1	203.6	Dried
8	1.0	22.4	Liquid[d]

a) Sludge was 50% anaerobically digested primary sludge and 50% aerobically digested waste activated sludge.
b) Filter cake sludge added to soil at 17% dry weight solids.
c) Dried sludge was air dried filter cake added to soil.
d) Liquid sludge added to soil at 6% dry weight solids.

The various soil treatments were added to plastic lined cardboard cartons (7.8 liters) at the rate of 2.27 kilograms per pot. No fertilizer additions were made; thus, the only nutrients available were from the sludge additions and the native soil (see Table 9). Water was added to field capacity.

The pots of treated soil were allowed to incubate for 0.5, 1, 3 and 6 months prior to seeding with wheat, sorghum sudangrass hybrid, or corn. After the selected incubation periods, 36 wheat, 36 sorghum sudangrass, or 16 corn seeds were planted by removing the proper depth of soil from the surface of the incubated pots. Seeds were distributed evenly and covered with soil. The pots were watered as needed to ensure adequate moisture for germination and growth.

Counts of the number of emerging seedlings and average plant height were made after 4 weeks. The pots were then thinned to three corn, four wheat, and four sorghum sudangrass plants and allowed to grow for the time intervals specified in Table 20. The plants were then harvested, dried at 60°C and weighed.

Table 20-Soil incubation periods and corresponding planting, thinning and harvest data

Incubation period	Date seeded	Date thinned	Date harvested	Growth period in days
2 weeks	4/5	5/1	6/20	76
1 month	4/19	5/21	6/20	62
3 months	6/21	7/12	9/13	84
6 months	9/27	10/25	12/12	76

Results and Discussion

The number of seeds that germinated and emerged after 1, 3 and 6 month pre-incubation periods are noted in Tables 21a, 21b and 21c, respectively. Germination data for the two week incubation period are not included because the seeds and emerging seedlings were consumed by mice. When this problem became evident screens were placed over the pots; thus, only the data from the one month and longer incubation periods are shown here.

Wheat was the least detrimentally affected by sludge additions, with germination essentially complete after two weeks. Sorghum sudangrass was the most adversely affected of the crops grown. Even the lowest sludge application had an adverse effect with the high rate of wet filter cake reducing germination rates by about two-thirds. Incubation periods longer than one month had some beneficial effect on sorghum sudangrass, but little effect on wheat and corn. This evidence would tend to indicate that at least part of the

Table 21a-The effect of sewage sludge on germination and emergence of seeds of three crops. Seeds planted one month after the treatments were mixed with the soil.

Treatment no.	Days after planting*				
	7	11	15	20	33
	Number of seeds germinated				
Wheat					
1	20	31	34	33	33
2	10	32	35	33	34
3	1	24	29	28	29
4	0	11	28	31	34
5	4	32	34	33	34
6	0	15	32	34	35
7	0	3	16	22	26
8	33	34	34	34	34
Sorghum sudangrass					
1	0	21	29	30	32
2	0	9	21	22	22
3	0	0	10	12	12
4	0	2	4	5	5
5	0	7	17	18	18
6	0	0	4	8	9
7	0	0	0	0	0
8	0	14	21	22	18
Corn					
1	0	9	16	16	16
2	0	11	16	16	16
3	0	3	11	14	16
4	0	2	6	6	12
5	0	1	8	16	16
6	0	1	4	10	12
7	0	0	4	5	5
8	0	16	16	16	16

* Counts were made on other days; however, the five reported in this table give the essential trends in germination and emergence.

Table 21b-Seeds planted three months after the treatments were mixed with soil

Treatment no.	Days after planting*					
	6	8	10	12	14	21
	Number of seeds germinated					
Lasso						
1	12	29	32	34	34	34
2	5	30	31	34	34	34
3	4	14	25	31	32	32
4	1	4	9	15	19	22
5	2	14	25	32	32	32
6	4	17	31	34	34	34
7	3	5	8	17	28	33
8	10	26	31	36	36	36
Sorghum sudangrass						
1	0	2	26	31	31	31
2	0	0	8	14	16	16
3	1	3	13	16	16	16
4	0	0	0	4	5	5
5	0	2	6	16	19	20
6	0	0	8	18	21	21
7	0	0	0	4	6	7
8	0	2	17	21	24	25
Corn						
1	0	3	16	16	16	16
2	0	6	5	16	16	16
3	0	2	10	16	16	16
4	0	0	0	7	7	8
5	1	3	9	16	16	16
6	0	1	8	15	15	15
7	0	0	4	10	12	12
8	0	2	10	16	16	16

* Counts were made on other days; however, the six reported in this table give the essential trends in germination and emergence.

Table 21.--Seeds planted six months after the treatments were mixed with soil

Treatment no.	Days after plantings: 5	7	9	11	14	22
	Number of seeds germinated[a]					
Wheat						
1	8	11	17	20	22	25
2	0	24	29	32	32	32
3	0	2	6	15	15	15
4	0	2	3	4	6	7
5	6	19	25	31	31	33
6	1	9	15	31	31	33
7	0	4	12	16	16	23
8	7	22	29	32	32	33
Sorghum sudangrass						
1	7	16	20	22	23	23
2	6	8	11	12	12	12
3	0	0	2	4	4	5
4	0	0	0	0	0	1
5	0	4	8	13	14	15
6	2	8	12	15	16	16
7	0	2	8	13	13	14
8	3	11	15	16	16	16
Corn						
1	1	6	10	16	16	16
2	0	5	8	15	16	16
3	0	0	1	4	6	6
4	0	0	1	4	6	6
5	0	9	12	16	16	16
6	0	3	6	13	14	15
7	0	2	8	10	13	14
8	1	6	10	16	16	16

[a] Counts were made on other days; however, the six reported in this table give the essential trends in germination and emergence.

inhibition of germination was due to some volatile component in the sludge, perhaps ammonia (NH_3). The wet sludge cake was the most inhibitive at one month, but this inhibitive effect was decreased either by drying prior to mixing with the soil, or after incubating in the soil for three to six months. Corn was intermediate in tolerance to germination inhibition, and was only adversely affected at the high rates of sludge addition.

Variations in germination counts within the controls and treatments were probably due to the fact that temperature within the greenhouse varied significantly and were generally below the optimum germination temperature for corn and sorghum sudangrass. The experiment was carried out in a carnation greenhouse where temperatures were regulated near 18°C.

Data showing early growth (centimeters of height) of seedlings after germination and emergence are shown in Table 22. Examination of these data indicates that the early growth rates were not consistently increased with increases in pre-incubation periods. As was generally true of the germination data, the one month and six month plant heights were often lower than the two week and three month plant heights. Evidently, the greenhouse environment played a significant role in the rate of growth of the seedlings. However, it can be seen that the height of the crops was appreciably influenced by the rate of sludge addition, which is most likely a reflection of rate of germination.

Pots were thinned to 3 or 4 average sized plants after approximately 4 weeks growth and allowed to grow another 2 to 3 months. The data showing the oven-dried weights of the harvested plant material are shown in Table 23. Since the growth periods were not the same for all four of the incubation period treatments (see Table 20 for growth periods) the yield data are not comparable except for the 76 day growing period for the plants in the 2 week and 6 month incubation periods. It appears that incubation of the soil-sludge mixtures for more than 2 weeks for wheat was not helpful. Corn and sorghum sudangrass showed increased yields with an incubation period of 3 months, however, there were no further increases in yield at 6 months. In fact, if the 6 month yield is compared with the 2 week yield for sorghum sudangrass and corn, both having growth periods of 72 days, it appears doubtful that there was an appreciable growth response for incubation periods longer than 2 weeks.

Conclusions

Treatments 1 and 8 had the best effects on the three biological parameters measured in this study with little difference between them. It is apparent that treatments 4 and 7 were the poorest. Thus, the wet sludge filter cake had the largest adverse effects on plant growth when compared on an equivalent weight basis to the dried sludge.

Sorghum sudangrass was the most inhibited by sludge additions, and was affected to some extent by all sludge treatments. Corn was intermediate in tolerance, and wheat was the least affected by sludge additions. There appeared to be no inhibition of germination and emergence of wheat and corn after an incubation period of 1 month, except for treatment 7 which continued to have inhibitory effects through 6 months of soil incubation.

Table 22-The effect of sewage sludge on early growth (two weeks after planting) of three crops grown in a greenhouse

Treatment no.	Incubation period: 0 weeks	1 month	3 months	6 months
	Seedling height in centimeters			
Wheat				
1	8.0*	10.0	10.0	10.0
2	7.8	7.8	10.6	10.1
3	7.1	5.0	9.0	5.6
4	6.0	3.4	9.6	5.0
5	3.6	6.2	7.4	7.0
6	3.4	2.3	7.0	6.0
7	0.6	0.6	4.6	6.0
8	6.0	10.0	9.6	11.2
Sorghum sudangrass				
1	1.2	1.6	5.0	5.1
2	2.0	1.0	1.7	5.7
3	1.3	1.0	2.3	2.0
4	1.5	0.2	1.0	3.2
5	0.3	0.3	1.0	7.0
6	0.2	0.1	1.0	4.0
8	**	**	0.4	4.6
7	1.4	1.5	3.1	7.4
8				
Corn				
1	3.0	4.2	9.4	4.4
2	4.3	3.2	7.0	3.5
3	2.2	1.5	0.4	1.3
4	4.5	0.5	3.0	0.7
5	0.7	0.5	0.0	2.5
6	0.6	0.2	0.3	2.5
7	0.1	.	2.7	2.1
8	3.2	4.6	8.6	6.0

* Data are mean values of 5 replicates.
** No germination.

Table 23-The effect of sewage sludge on oven dry weight of three crops grown in a greenhouse for 2 to 3 months

Treatment no.	Incubation period			
	2 weeks	1 month	2 months	3 months
	Yield (grams/pot)			
Wheat				
1	1.41	0.47	0.67	1.46
2	3.36	1.68	0.99	0.90
3	2.36	0.56	2.57	0.81
4	2.22	0.17	1.75	0.93
5	2.36	0.89	1.30	0.66
6	2.49	0.13	0.99	0.70
7	0.67	0.14	1.15	0.32
8	3.30	1.12	1.69	1.05
Sorghum sudangrass				
1	0.29	1.43	0.79	1.22
2	0.21	0.92	1.31	0.31
3	0.12	0.39	1.78	0.58
4	0.07	0.06	0.21	0.14
5	0.06	0.21	1.60	0.31
6	0.12	0.08	1.58	0.40
7	0.06	*	0.79	0.08
8	2.91	1.06	2.30	0.96
Corn				
1	0.93	1.40	2.12	2.35
2	2.21	1.29	2.48	2.16
3	0.37	0.75	2.14	0.69
4	0.57	0.80	1.83	0.57
5	0.32	0.71	2.58	1.15
6	0.07	0.40	1.95	0.55
7	0.64	0.12	0.82	*
8	2.81	2.00	3.16	2.46

* No plants harvested.

The dried sludge had less inhibition than equivalent weights of wet filter cake on emergence and subsequent early plant growth.

Ambient temperatures of the greenhouse used for this study were too low for adequate germination and growth of sorghum sudangrass, plus the loss of seeds and some plants to hungry mice made interpretation of these data difficult. It appears, however, that the effects of sewage sludge additions were more inhibitive to sorghum sudangrass germination and emergence than to corn or wheat.

SLUDGE AIR DRYING PROJECT

If liquid sludge is transported from the treatment plant by conventional truck transport, energy requirements are extremely high and the cost of haul becomes rapidly prohibitive with increasing distances from the treatment plant. While removal of some of this water by vacuum filtration reduces hauling costs, the total costs are still extremely high.

Metro has been investigating pipeline transport of liquid anaerobically digested sewage sludge to a remote area where the sludge could be air dried and subsequently utilized as an agricultural product. This method would not only avoid expensive haul and vacuum filtration costs, but would also provide a valuable agricultural product.

A research project examined the possibilities of drying liquid sludge in shallow, earthen drying basins. Parameters measured were water loss through soil percolation and/or evaporation, nitrogen losses and the development of odors or undesirable vectors, i.e. flies or rodents.

Materials and Methods

Five drying basins were built at the CSU Agricultural Experiment Farm at Fort Collins. The basin dimensions were 7.6 centimeters x 9.14 meters x 1.2 meters in depth. Anaerobically digested liquid sludge (approximately 5%) from the East Drake Wastewater Treatment Plant in Fort Collins was added to the basins on August 7, 1973 to depths of 25.4, 50.8, 76.2 and 101.6 centimeters (Table 24). The basins did not have underdrains, and basin E was lined with plastic to prevent water losses due to percolation. Basin G was filled with 101.6 centimeters of anaerobically digested liquid sludge on January 16, 1974 to determine drying rates and nitrogen losses during winter months.

Water loss was determined daily by measuring the level of the liquid sludge in the drying basins. Percent TS were determined weekly. Determinations of TKN, NH_4-N and NO_3-N were made weekly. Zinc, Cu, Mn and Fe are reported as DTPA extractable metals. Available P was determined by extraction with ascorbic acid. Potassium was analyzed by extracting with normal NH_4OAC.

Results and Discussion

Basin A to which 25.4 centimeters of sludge were applied, dried from about 5%

TS to about 50% to 60% solids in a 1 month period (Table 25). Basin B to which 50.8 centimeters of sludge were applied, dried to 40% TS in a 4 month period. None of the other basins dried during the duration of the experiment (10 months). It is interesting to compare basin B (unlined) with basin E (lined). Both basins received 50.8 centimeters of sludge, however, the latter basin showed more dilute solids concentration in January 1974 than when it was originally loaded in August 1973. This demonstrates that most of the water loss was due to percolation into the soil rather than evaporative losses, and that during the winter months precipitation exceeded evaporative losses.

Table 24-Initial depth of liquid sludge

Basin	Liquid sludge depth (cm)
A	25.4
B	50.8
C	76.2
D	101.6
E*	50.8
G	101.6

* Basin E was lined with plastic to prevent water losses from percolation.

Table 25-Change in percent total solids content of drying basin with time

Basin	Sampling Date 8/73 % Total solids	1/74
A	4.6	61.7
B	4.6	40.3
C	4.2	13.9
D	4.2	7.5
E	4.2	3.3

The Fort Collins Agricultural Experiment Station has a permanent meteorological station where pan evaporation and precipitation are accurately measured. Data from this station indicated that:

A) Net evaporation (evaporation minus precipitation) occurred during the months of June through December.

B) Negative evaporation (excess of precipitation over evaporation) occurred during January through May.

C) Total precipitation (rain and snowfall) averaged 2.8 centimeters per month for a total of 34.0 centimeters between October 1972 and September 1973.

D) Gross evaporation totaled 92.7 centimeters.

E) Net evaporation totaled 58.7 centimeters.

F) Precipitation during the 7 driest months (June through December) totaled 20.3 centimeters.

G) Gross evaporation during the 7 driest months (June through December) totaled 58.4 centimeters.

H) Net evaporation during the 7 driest months totaled 38.1 centimeters.

By comparing these data with a desired sludge cake end product of at least 40% TS for subsequent stockpiling, it is theoretically possible to establish the optimal sludge loadings for any particular season. Table 26 summarizes the net evaporation requirements over a 12 month and 7 month period at loading rates between 15.24 and 121.92 centimeters per application. Based on the 1973 through 1974 meteorological data there is a net evaporative rate of 58.7 centimeters per year. Then the maximum liquid sludge depth possible for a 40% TS sludge cake equals 65.0 centimeters. The 7 driest months of the year (June-December) have a net evaporative rate of 38.1 centimeters; thus, the maximum liquid sludge load possible for obtaining a 40% TS sludge equals 42.3 centimeters.

It should be pointed out that these are hypothetical figures based on evaporation of pan water. Water obtained in partially dried sludge will be under capillary forces; therefore, decreasing the net evaporative effect.

One of the problems associated with drying the sludge was the development of a thin, dried sludge crust on the basins' surfaces. The hydraulic conductivity of this dried crust is severely reduced, preventing the capillary movement of water to the surface from the saturated sludge below. The effect of this crust is evident when the TS content of basin B is compared with basin E. Basin E was lined with plastic; therefore, all water losses were from evaporative losses. Because of this crust development basin E did not dry. Basin B lost water through percolation rather than evaporation. Another approach being studied is the addition of thin layers of liquid sludge (0.6 centimeters per application). In this way it is hoped that there will be no significant crust development covering a pool of liquid sludge.

The odor level was not usually significant except for a brief period. The most intensive odors were encountered after the spring thaw of frozen sludge in the drying basins. There were neither odor nor other nuisance complaints by any of the neighbors. Many small flies or gnats accumulated over the basins during the last half of August, but did not assume nuisance proportions.

Table 26-Net evaporation required (centimeters per year) at various sludge loading rates

Variables	Sludge loadings in cm/year				
	15.24	30.5	61.0	91.4	121.9
Water load @ 4% TS (cm)	14.7	29.2	58.4	87.5	117.1
Precipitation 1973-1974 (cm/yr)	34.0	34.0	34.0	34.0	34.0
Total water load (cm/yr)	48.7	63.2	92.4	121.5	151.1
Final sludge volume required @ 40% TS (cm)	1.5	3.0	6.1	9.1	12.2
Gross evaporation required (cm/yr)	47.2	60.2	86.4	112.5	144.0
Precipitation June-December (cm/season)	20.3	20.3	20.3	20.3	20.3
Total water load (cm/season)	35.1	49.5	78.7	108.3	137.4
Final sludge volume (cm) required @ 40% TS	1.5	3.0	6.1	9.1	12.2
Gross evaporation required (cm/season)	33.5	46.5	72.6	99.1	125.2

Chemical data indicated that the sludge lost considerable quantities of extractable NH_4-N (from about 5,000 ppm to 2,000-3,000 ppm) but little NO_3-N accumulated in the sludge. Apparently, NH_4 was volatilized or nitrified, and the NO_3 was denitrified below the surface.

On January 15, 1974 101.6 centimeters of anaerobically digested sludge (approximately 71,000 liters) from the Fort Collins Sewage Treatment Plant were loaded into a lined drying basin (designated basin 6). A sampling program was designed to obtain weekly samples from three locations at three different depths for nitrogen analysis. Table 27a summarizes the nitrogen concentrations while Table 27b summarizes the nitrogen concentration as a percent of the total solids concentration of the three stratified samples.

Within 4 weeks of the initial loading approximately 30% of the TKN was lost. Most of this loss occurred in the bottom and middle layers of the stratified basin, and changed little thereafter. Within 6 weeks of the initial loading, approximately 75% of the NH_4-N had been lost and again most of the loss occurred in the bottom and middle layers. During the sixth week, solids from the bottom layer floated to the top stratum which tended to raise the N concentrations of the top and middle layers.

The variations in other chemical determinations followed no definite pattern, neither increasing nor decreasing with time, and are shown in Table 28.

Table 27a-Nitrogen concentration of 3 layers of liquid sludge in drying basins[a]

Date sampled	mg/l NH3:N bottom	NH3:N middle	NH3:N top	TKN bottom	TKN middle	TKN top	NO3:N bottom	NO3:N middle	NO3:N top
1/23/74	2,850	3,230	530	4,500	4,710	644	0.50	1.05	0.45
2/5	1,300	1,340	1,000	2,930	2,720	564	0.05	0.20	0.25
2/12	700	750	560	3,250	2,910	716	2.20	2.35	0.01
2/19	740	750	675	2,860	3,040	536	0.30	0.50	0.45
2/16	725	700	450	3,000	2,150	448	0.20	0.40	0.10
3/5	700	750	700	2,640	2,690	1,650	0.65	0.65	1.60

Table 27b-Nitrogen concentration as a percent of the total solids concentration of the three stratified samples

Date sampled	% NH3:N bottom	NH3:N middle	NH3:N top	TKN bottom	TKN middle	TKN top	NO3:N bottom	NO3:N middle	NO3:N top
1/23/74	6.5	9.0	11.3	9.8	13.1	12.4	N[a]	N	N
2/5	8.2	8.7	14.5	9.2	8.6	9.5	N	N	N
2/12	1.3	1.4	11.0	5.3	5.2	11.9	N	N	N
2/19	1.3	1.3	11.3	5.2	3.2	10.6	N	N	N
2/26	1.3	1.2	10.0	5.6	3.6	9.8	N	N	N
3/5	1.2	1.3	1.8	4.4	4.6	4.1	N	N	N

[a] N mean negligible.

Table 28-Range in various chemical constituents of liquid sludge contained in drying basins

Chemical constituent	Range
% Volatile solids	48 - 70
Conductivity mmhos/cm	4.5 - 7.1
pH	7.2 - 8.5
P* (ppm)	650 - >1000
K** (ppm)	690 - >1000
Zn*** (ppm)	285 - 505
Cu (ppm)	34 - >50
Fe (ppm)	150 - 310
Mn (ppm)	4.8 - 11.4

* Sodium bicarbonate extractable P.
** Ammonium acetate extractable K.
*** DTPA extractable Zn, Cu, Fe and Mn.

Conclusions

This study indicated that earthen drying basins with more than 50.8 centimeters of sludge will not dry rapidly enough to allow yearly removal of dried sludge. Comparisons of lined and unlined basins demonstrated that most of the water loss was through soil percolation and not evaporation. The formation of a thin dried sludge crust prevented evaporation from taking place at the sludge surface. If this sludge crust could be constantly broken up and reincorporated into the wet sludge or prevented from forming through applications of thin layers of liquid sludge, it would be theoretically possible to dry as much as 43.2 centimeters of liquid sludge per year. During the drying process, about 40% of the total N content is lost through leaching, volatilization or denitrification.

FUTURE AGRICULTURAL RESEARCH AND DEVELOPMENT PROJECTS

In 1975, a comprehensive $418,000 research program consisting of 10 projects was approved by the Metro Board of Directors. This agricultural research program was designed to obtain additional information on various aspects of sludge recycling to land, and to answer some of the questions raised in the Environmental Protection Agency Technical Bulletin No. 430/9-75 titled "Acceptable Methods for the Utilization or Disposal of Sludges". The projects included:

1. Investigation of drying basin optimization.
2. Sludge characterization to define chemical and biological constituents of Metro sludge.
3. Investigation of detention times and other conditions required to reduce to acceptable levels viruses and other potential pathogens.
4. Nitrogen management to enhance or diminish nitrogen concentration in sludge depending on intended use.
5. Greenhouse and crop rotation study.
6. Heavy metals monitoring.
7. Heavy metals monitoring of soil receiving cumulative sludge loadings.
8. Subsurface injection of liquid sludge.
9. Mine tailing reclamation.
10. Investigation of heavy metals as it effects the food chain from sludge to the tissues of animals grazing on vegetation grown on a sludge-soil mixture.

Metro is also working with the U.S. Geological Service and the Colorado State Geologist Office to investigate the effect of heavy loadings of sewage sludge conditioned with chemicals on ground water at the Lowry Bombing Range.

A summary of project objectives and scope of work follows.

DRYING BASIN PROJECT

Objective

To obtain information on a continuous loading basis required for development of a relatively problem-free operations scheme to manage 600 acres of drying basins at the proposed sludge drying and distribution site.

Scope of Work

1. Anaerobically digested liquid sludge (primary and mixed primary plus secondary) are being added to earthen drying basins to determine optimum loading rates and drying times.

2. The loading rates are intended to simulate fullscale loading rates to basins at a sludge drying and distribution center.

3. Four separate drying basins, each 0.1 hectares, are being utilized. The basins are unlined and without underdrains.

4. Acceleration of drying rate of 101.6 centimeters of sludge is being investigated by:

   A) Decanting supernatant liquor (less than 1.0% total solids).

   B) Mechanical agitation using surface drag.

5. Special emphasis will be placed on evaluating seasonal effects as they relate to hindrance of drying with each successive liquid sludge loading to previously dried sludge.

6. Information obtained from successive loadings will be used to determine strategy for dried sludge removal and storage.

7. The practical problems involved in removing thin layers of dried sludge mixed with soil will be investigated.

8. The Northern Colorado Research Demonstration Center (NCRDC) at Greeley, Colorado is the site for this investigation. The research farm provides an excellent demonstration to the farm community of the benefits of this project.

9. Each basin is being monitored for:

   A) Water loss by percolation.

   B) Quality of the water percolating through the soil profile.

   C) Nitrogen changes in the sludge as a function of drying time.

   D) Odors and vectors.

f) Change in soil permeability with successive applications of liquid sludge.

10. The Fort Collins treatment plant is the source of liquid anaerobically digested primary plus secondary sludge, while the Denver North Side Treatment Plant is the source of anaerobically digested primary sludge.

11. The air dried sludge will be cured in a stockpile for several months. The effect of drying time on pathogen reduction will also be monitored.

SLUDGE CHARACTERIZATION

Objective

1. To obtain data concerning concentrations and seasonal variability of those parameters (heavy metals, nutrients, etc.) used by regulatory agencies to establish guidelines for land application of stabilized sludge.

Scope of Work

1. Metro laboratory is analyzing monthly composite sludge samples for fertilizer elements (TKN, NH_4, total P and total K) and heavy metals (total Zn, Cu, Ni, Cd, Pb, Cr).

PATHOGEN STUDY

Objective

1. To determine relative concentrations and variability in the anaerobically digested sludge of certain viral and parasitic organisms having public health significance.

2. To determine the survival rate of the pathogens in the soil-sludge mixture. Particular emphasis will be placed on the minimum detention time required between sludge application to land and the growth of crops destined for human consumption.

Scope of Work

1. The Biological Waste Management and Soil Nitrogen Laboratory of the Agricultural Research Service at Beltsville, Maryland will provide the analytical services and research direction for this study.

2. Survival rates of endemic salmonellae and ascaris ova in digested sludge as it is dried and stockpiled will be determined to estimate the air drying or storage time needed to eliminate these organisms.

3. Sewage sludge at the treatment plant will be seeded with f2 bacteriophage. The survival of f2 bacteriophage, which closely resembles the enteroviruses (poliovirus, coxsackievirus, echovirus and reovirus) physiologically, will be examined to estimate the survival rates of other viruses which are difficult to impossible to identify in sludge.

4. The liquid sludge will be applied to the sludge drying beds at Greeley, Colorado. Samples of the sludge will be collected every 2 weeks for pathogen and virus analysis.

5. Sampling will continue long enough to establish the survival times of the organisms.

NITROGEN MANAGEMENT PROJECT

Objectives

1. To prevent nitrate pollution of ground waters.

2. To maintain the nitrogen fertilizer value in the sludge that is to be marketed.

Scope of Work

1. The staff of the Department of Agronomy at CSU will conduct the laboratory phase of this project during the first year.

2. Upon successful completion of the laboratory phase of this study, a second phase field experiment may be recommended to verify on a large scale results obtained from the lab study.

3. A laboratory bench anaerobic sewage sludge digester has been fed N^{15} enriched ammonia in order to incorporate the labeled nitrogen isotope into both the organic and inorganic nitrogen compounds of the digested sludge.

4. The N^{15} enriched sludge will be added at various loading rates to soil. After suitable detention periods, the soil-sludge mixture will be quantitatively analyzed for NH_4, NO_3, N_2O, NO and N_2 by mass spectrometry. This analysis will determine the rate of denitrification occurring in the soil-sludge mixture.

5. Gas samples will be taken from enclosed incubation vessels for determining CO_2, CH_4, NO, N_2O and N_2 gas production. A comparison of gas chromatography and mass spectrometry results will enable determination of kinetics of mineralization, nitrification and subsequent denitrification of organic nitrogen forms.

GREENHOUSE AND CROP ROTATION STUDY

Objectives

1. To determine the influence of anaerobically digested sludge at various loading rates on germination, growth and yields of crops grown in Colorado.

2. To apply information obtained from greenhouse tests for validation in the field under varying crop rotation schemes typical of farm practice in Colorado.

3. To determine the extent to which anaerobically digested sludge may be substituted (in whole or in part) for other types of commercial or organic fertilizers as presently used by the farm community.

Scope of Work

1. The greenhouse portion of this study will be conducted during two seasons, namely:

   A) Cold weather germination (18.5°C ± 2°).

   B) Warm weather germination (24°C ± 2°).

2. The crops to be studied during the cold weather phase of the greenhouse study include sugar beets, wheat and barley. The crops to be studied during the warm weather phase include pinto beans, corn and sorghum sudangrass. The study began in 1975 and will continue for two years.

3. Sludge loading rates of 0, 22.4, 44.8 and 90 metric tons per hectare equivalent are being tested with detention times of 0, 2, 4 and 8 weeks between sludge application and seeding.

4. Greenhouse data analysis will stress effects of various loadings and detention times upon germination rate and growth rate (height versus time).

5. Concurrent with the greenhouse study, field test loadings of 0, 15.7, 31.4, 47 and 94 dry metric tons per hectare of anaerobically digested sludge have been applied to a field test site at the NCWRC at Greeley. The field trial began in March of 1975. Total duration of the crop rotation cycle is 2 to 3 years.

6. The crops being grown are corn, beans and sugar beets, which will be rotated in the second and third years of the experiment.

7. Field crop rotation data analysis will compare yields of the various crops to loadings of sludge versus commercial fertilizer. The harvested crop will be analyzed for nutrient and heavy metals content.

8. Soil analysis is being performed on all plots prior to and after each growing season to determine total nutrient loadings of sludge and/or commercial fertilizers which will then be correlated to crop response.

HEAVY METALS UPTAKE

Objectives

1. To determine the uptake of heavy metals (Zn, Cu, Ni, Cd, Cr and Pb) into crops commonly grown in Colorado.

2. To determine the extent to which heavy metals become more available or less available to crops after sludge application to soil.

Scope of Work

1. Two rates of sludge (336 and 670 dry metric tons/hectare) have been added to experimental plots at the NCREC at Greeley, Colorado. Total DTPA and water extractable soil metals are being correlated with plant uptake and possible yield depression.

2. Metal salts equivalent to 336 and 670 metric tons/hectare have been added to additional plots to compare availability of sludge born metals to metals in soils without organic matter additions in relation to plant uptake.

HEAVY METALS MONITORING PROJECT

Objectives

1. To determine the long-termcumulative effects of repeated applications of sludge on buildup of toxic metals in soil or plant material at the Watkins research site.

Scope of Work

1. The 0.8 hectare site consists of 72 plots. Thirteen of the plots have never received sludge and are used for baseline data comparisons. Loadings of sludge between 20 and 200 dry metric tons per hectare were applied during the first year (1971) to 59 plots. The sludge was subsequently incorporated into the soil by discing and plowing.

   During the second year (1972) liquid sludge loadings between 20 and 43 dry metric tons per hectare were applied by subsurface injection to 32 of the 59 plots that received sludge in 1971.

   During the third year (1973) no sludge was applied to any of the 72 plots.

   During the fourth year (1974) liquid sludge was applied by subsurface injection to 36 of the original 59 plots receiving sludge in 1971 at loadings between 11.2 and 22.4 dry metric tons per hectare.

2. The Watkins research site monitoring will be continued for another 2 years until the full scale drying distribution site is in operation. The decision to phase out the Watkins site will be determined by the analytical re-

sults obtained during this period.

3. Winter wheat will be planted annually on all of the 72 test plots. Supplemental irrigation will be provided as necessary to ensure germination and growth despite fluctuations in precipitation.

SUBSURFACE INJECTION PROJECT

Objectives

1. To develop backup technology to the air drying system capable of year around handling of anticipated sludge production at the full scale reuse site. Particular emphasis will be placed upon injection into frozen soils.

2. To demonstrate the technical and economic advantages of subsurface injection for liquid nutrient application and crop growth.

Scope of Work

1. The duration of this project is anticipated to be 2 years (1976-1977).

2. Metro will purchase or lease existing injection equipment for both shallow and deep (0.3 to 1 meter) injection. This equipment will be modified as required to ensure frozen ground capability, uniformity of sludge distribution and minimizing power requirements for either beneficial recycle or disposal modes of operation.

3. The nearest recommended injection site available is at the LBR. Eleven hectares of land which has never received sludge will be used for this purpose.

4. The liquid sludge will be transported from the central plant to Lowry by means of a 5,000 gallon tank truck which will then be connected to the subsurface injection device by a hose. The subsurface injector will be pulled by a tractor.

5. Effects of subsurface injected liquid sludge on yield will be evaluated for native pasture land and winter wheat.

6. Soils and foliage will be analyzed for nutrient and heavy metals content.

MINE TAILING RECLAMATION PROJECT

Objectives

1. To demonstrate the beneficial effect of applying anaerobically digested sludge for reclamation of rock and mine tailings in forested mountain areas of Colorado.

Scope of Work

1. The site being investigated is located at the base of Berthoud Pass at the recently abandoned Urad molybdenum mine. Approximately 100 hectares of mine tailing wasteland will require reclamation over the next few years.

2. During 1975, approximately 12 hectares of tailings received a mixture of sludge and wood shavings. During 1976-1978 20 hectares per year will be reclaimed requiring approximately 2,240 dry metric tons per year of sludge from Metro. Growth response and environmental factors will be evaluated.

ANIMAL UPTAKE PROJECT

Objectives

1. To determine whether and to what extent contamination of tissues in cattle grazing sludge applied land has occurred which could represent a hazard to human health.

Scope of Work

1. Representative mature beef cattle from the LBR sludge recycle site and from a control herd have been slaughtered. Tissue analysis of liver, kidney, muscle, blood, bone, fat and brain is presently being analyzed for heavy metals and toxic organics.

2. An extensive survey of sludge, soil and vegetation at the LBR and a control site is presently underway. Samples are being analyzed for the same chemical constituents being determined in the animal tissues.

3. Beef cattle similar to those at the LBR have been fed Metro Denver sewage sludge as a percentage of their diet to determine the effect of direct ingestion of larger amounts of sewage sludge on edible animal tissues.

GROUND WATER QUALITY AT THE LOWRY BOMBING RANGE

Objectives

1. To investigate the effects that sludge disposal at the LBR has had on ground water quality.

Scope of Work

1. Determine the location and extent of alluvial aquifers, direction of ground water movement in the shallowest bedrock aquifer. This is being accomplished by drilling some 60 wells at various depths in and around the sludge recycle site.

8. Quality of ground water upgradient and downgradient from the recycle site is being monitored for pathogens, alkalinity, sulfates, chlorides, phosphates, nitrogen, COD, organic carbon, dissolved solids, hardness and metals (Na, K, Ca, Zn, Fe, Pb, Cr, Cu, Ni, Mn, Cd).

SUMMARY AND CONCLUSIONS

Processing and ultimate disposal of wastewater sludge is one of the most costly unit processes within any sewage treatment plant. Since 1969 Metro has been examining methods of sludge disposal which are economical and environmentally safe. Prior to 1969, all of the sludge produced by Metro was either flash dried, incinerated, or lagooned. The dried material was used as a fertilizer on city parks, while the incinerated material was landfilled. However, due to continuous mechanical and air pollution problems the flash dryer-incinerator units were permanently shut down in August of 1971.

Since 1971 the only mode of sludge disposal used by Metro has been land application. A number of different disposal procedures have been tried over the intervening years.

During 1969 and 1970 the vacuum filter cake sludge, which could not be processed by the FDI units, was transported by truck to the LBR. Two methods of incorporation were utilized, one for dry weather and the second for wet weather. Dry weather operations consisted of tailgating the sludge directly from the transport vehicle onto the soil surface. The sludge was then thinly spread over the surface with a front mounted blade on a dozer. The sludge was allowed to dry for 24 hours and then rototilled in. This operation was not always satisfactory because large rocks, dense vegetation, or wet soil would clog or render the rototiller inoperable.

During wet weather, or when the ground was frozen, sludge was mixed directly into the soil using a front mounted blade on a dozer. A satisfactory mix was accomplished when approximately 5 parts of soil were mixed with 1 part of sludge. However, this operation was not satisfactory due to the economics of a 24 hour per day operation and its inherent difficulty.

Because of these problems, several changes in sludge application methodology were adopted. At the LBR site a ramp was constructed which allowed the transport vehicles to load sludge directly into farm manure spreaders. The sludge was then spread onto native pasture land at the rate of about 6.7 metric tons per hectare. After the sludge had dried, about a half hour, a spiked tooth harrow was used to break any large clumps of sludge into fine particles. This method proved satisfactory for one year, however, during the late spring of 1972 when the area had dried, small smoldering fires started in the areas which had received many consecutive sludge applications, a result of careless smokers and heavy equipment operating in the area. These fires proved difficult to extinguish, particularly in high winds. Other problems arose when the contractor experienced difficulty with access to the field. As a result, large quantities of vacuum filter cake were stockpiled to a depth of about 1.2 meters in a depression. Shortly thereafter snowstorms covered the stock-

piled filter cake. As the snow began to melt, the waste activated and raw primary sludge began to decompose creating odor nuisances to residents living adjacent to the area.

Because of the fire and odor nuisances a new method of land application was started in June of 1972. The sludge was spread 5 to 8 centimeters in depth and then plowed under within 6 hours of application. Crops such as wheat, oats or sudangrass were planted to reduce soil erosion, and to provide forage for the cattle that continuously grazed the land. This method has been providing satisfactory control of odor and fire problems since 1972.

Special modifications were adopted during winter operations when the soil is frozen and cannot be plowed. Since 1973 an inclement weather site has been prepared in advance by bench and terracing the area. Inclement weather operations generally take place during December, January and February, depending upon the severity of the winter. During the relatively mild, dry winter of 1974-1975 the inclement weather site was required for only 30 days during January and February.

Vacuum filter cake sludge disposed of at the LBR is a mixture of raw primary, waste activated and anaerobically digested primary sludge. Continuous sludge loadings since 1969 have increased the N content of the soil to excessive levels beyond any capacity for crop removal. However, this may not pose a serious threat to ground water quality due to the fact that rainfall is limited and the potable ground water is protected for the most part by impervious stratum within the regolith.

Sludge additions have increased the K, P, salt and organic matter content of the LBR soils, but not to levels that could be considered excessive or out of the normal for agricultural soils in this area. The heavy metal content has increased significantly, whether this has been detrimental to crop growth is unknown. However, it is doubtful since tissue analysis of plant samples has not shown levels that would be considered out of the normal elemental composition range for plant materials.

By 1971 it became apparent that land application of wastewater sludge was not going to be a temporary expedient, but rather a long term necessity. Therefore, a number of studies were entered into to evaluate the effects of sludge on environmental concerns and crop response.

A field experiment was set up at Watkins, Colorado to evaluate the effects of various sludge loadings on crop germination and subsequent growth. Results indicated that there was a severe inhibition of germination when millet or sorghum sudangrass were planted immediately after sludge incorporation. However, this inhibition was eliminated when the sludge was allowed to incubate in the soil for two months. Wheat yield data showed increased yields with application rates of 25 and 50 dry metric tons per hectare.

Microbial counts taken 6 months after sludge incorporation demonstrated that there were no differences in fecal coliform bacteria between the sludged plots and the control plots.

The studies conducted at Watkins led to a greenhouse investigation in which a number of soil sludge mixtures were utilized to evaluate the effects of various incubation periods on germination and plant growth. Results demonstrated that sorghum sudangrass was inhibited the most by sludge additions, while corn was intermediate in tolerance, and wheat was the least affected of the three crops tested. There appeared to be no inhibition of germination and emergence of wheat and corn after a soil sludge incubation period of 1 month. Of the sludge types used, dried sludge had the fewest adverse effects on germination.

Metro has been investigating the possibilities of air drying liquid anaerobically digested sewage sludge in shallow, earther drying basins. Data collected from experimental drying basins demonstrated that more than one-half of the N content of the sludge is lost during the air drying process. Comparisons of plastic lined and unlined basins demonstrated that most of the water is lost through soil percolation and not evaporation.

It is important to realize that the recycling of organic matter is not a new process, but one that has been occurring for eons, since the beginning of life itself and is essential for its very maintenance. Organic matter represents a stockpile of energy, one that should not be wasted. With the realization that fossil fuels (recycled organic matter) are coming in short supply, it becomes evident that to waste any source of energy is self defeating. It is interesting to note that the word waste is often applied to human and animal excreta when in a biological sense it is not a waste. In fact, the only justification for the term "waste" is that a potential source of energy has been wasted.

Unfortunately, there are problems associated with the recycling of sewage sludge. Much of our sewage is not derived from garbage or fecal material, but is the product of industrial waste. Modern society tends to centralize and concentrate industry, which is reflected in the wastewater treatment plant. Thus, metals or exotic organic compounds such as pesticides which are products or by-products of industry turn up in sewage sludge. In addition to these elements and compounds there is a disease hazard. The problems in dealing with these elements, compounds and biological agents become particularly acute when sludge is to be recycled into agriculture and the food chain.

If sewage sludge is to be utilized as an agricultural resource, the authors of this report feel that there are a number of areas which will require future research efforts. These include public health aspects, plant response and food chain effects from heavy metals, the true fertilizer value of sewage sludge as measured by crop response, and particularly, public awareness or acceptance of sludge as a resource.

Under the heading of public health aspects fall a number of issues or problems. The most immediate is whether or not utilization of sewage sludge on agricultural land represents a health hazard. Pathogens are known to survive the sewage treatment process, but the threat to public health has not been adequately evaluated. Research efforts are needed to determine the survival rates of enteric pathogens (parasites, bacteria and viruses).

Since there is the possibility that cattle may ingest quantities of sludge, i.e soil or from dust on forages, the health effects on livestock or humans consuming the livestock should be evaluated.

Another public health aspect would have to include possible food chain effects of heavy metals on crops, animals, and humans. Little is known about the tolerance or uptake rates of plant species and varieties under different soil, climate and management practices. Metals that should be studied include As, B, Cd, Cr, Cu, Hg, Ni, Pb, Se, and Zn because of their potential toxicity to plants or hazard to livestock and humans.

If sewage sludge is to be handled as a resource, specific data evaluating its effects on crop yield and quality should be made available to the potential user. Responses of various crops should be evaluated for different management practices which would include loading rates, soil pH levels, climate, irrigation or water relationships, timing of application, methods of incorporation different forms of sewage sludge (i.e. dried, liquid, dewatered), and rates of nutrient removal or availability.

And finally, the public will have to be educated and made aware of the economical and ecological advantages of recycling sewage sludge in order to counter existing cultural prejudices against wastewater sludge.

[illegible]

Table 25-Analysis of Dairy Basking Range soils samples spring of 1972

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Table 38—Analysis of Lowry Washing Range soils sampled spring of 1923

Table 3b—continued

[illegible]

Table 3—continued

Table 2--continued

Table II—continued

Stratum	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

[illegible]

REFERENCES

1. Soil Conservation Service, 1971. Soil Survey Arapahoe County, Colorado, United States Department of Agriculture.

2. Soil Conservation Service, 1974. Soil Survey Adams County, Colorado, United States Department of Agriculture.

3. Jackson, M.L., 1958. Soil Chemical Analysis. Prentice Hall, Inc., Englewood Cliffs, New Jersey.

4. Watanabe, F.S. and S.R. Olsen, 1965. Test of an Ascorbic Acid Method for Determining Phosphorus in Water and NaHCO3 Extracts from Soil. Soil Science Soc. Amer. Proc. 29:677-678.

5. Pratt, P.F., 1965. Potassium. In C.A. Black (ed.) Methods of Soil Analysis, Part 2-Chemical and Microbiological Properties, Chapter 71, p. 1026.

6. Lindsay, W.L. and W.A. Norvell, 1969. Development of a DTPA Micronutrient Soil Test, Agron. Abstr.

GLOSSARY

B	boron
Ca	calcium
Cd	cadmium
CEC	cation exchange capacity
Cl	chlorine
cm	centimeters
COD	chemical oxygen demand
CSU	Colorado State University
Cu	copper
DTPA	diethylenetriaminepentaacetic acid
FDI	flash dryer-incinerator
Fe	iron
FeCl3	ferric chloride
g	grams
ha	hectare
K	potassium
kg	kilograms
LBR	Lowry Bombing Range
Metro	Metropolitan Denver Sewage Disposal District No. 1
Mg	magnesium
MGD	million gallons per day
µmho/cm	micro mho per square centimeter
mmho/cm	milli mho per square centimeter
Mn	manganese
Mo	molybdenum
N	nitrogen
Na	sodium
NCRDC	Northern Colorado Research & Demonstration Ctr.
NH_3	ammonia
NH_4	ammonium
NH_4-N	ammonium nitrogen
NO_3	nitrate
NO_3-N	nitrate nitrogen
OM	organic matter
P	phosphorus
Pb	lead
pH	negative logarithm of the hydrogen ion activity
ppm	parts per million
TKN	total kjeldahl nitrogen
TS	total solids
Zn	zinc